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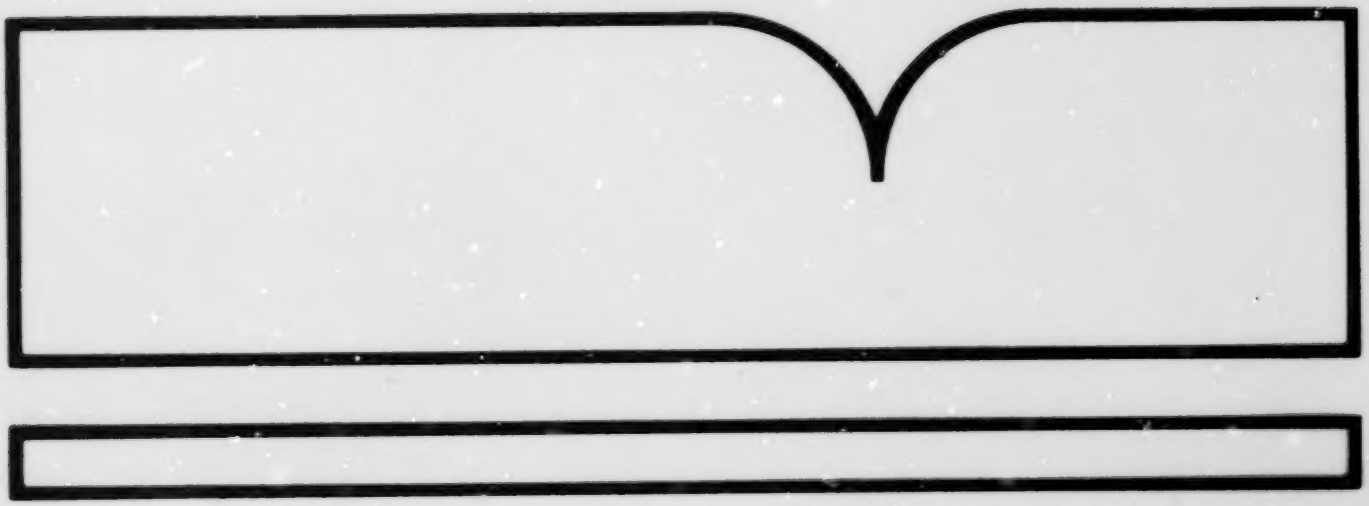

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STRATEGIES FOR THE DEVELOPMENT OF CLIMATE SCENARIOS FOR IMPACT ASSESSMENT

PHASE 1

FINAL REPORT

by

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In order to create a strategy for the development of climate scenarios for use in impact assessment, potential techniques of development were reviewed and the information needs of potential users assessed. Available techniques were assessed through literature reviews and consultations with scenario development experts. Techniques were divided into ten modules, groups of techniques with similar methodologies, input requirements and output formats. Three modules involve approaches which model atmospheric processes, four concern analysis of past climate records, and three concentrate on methods for linking the other two. Each module can provide a scientifically well-founded piece of needed information, and a series of modules used together will produce the scenario. User needs were assessed in consultation with selected individuals who had experience in the use of scenarios. The major needs were revealed to be for general descriptive statistics of the major climatic elements, for information about climatic anomalies, notably drought, for statistics on the frequency and probability of events exceeding particular thresholds, and for general information about storminess. The results of the two sets of assessments are combined to provide a scenario development strategy. An iterative approach is recommended. Project areas incorporating both scenario development efforts and fundamental research are identified for the first three iterations.

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FOREWORD

The need for scenarios of possible future climate conditions prior to any assessment of potential climatic impacts is becoming increasingly clear. While some scenarios are available, they have been for a restricted range of impacts and have used a small number of techniques. There has been no comprehensive review of all possible scenario development techniques, nor of the needs of the impact assessors who will use the scenarios.

Thus this document is designed to survey the range of potential approaches to scenario production and to assess the information needs of scenario users. It provides the technical background needed to guide EPA program managers in the development of a research strategy which leads to the production of scientifically sound climate scenarios.

Peter Robinson
Peter Finkelstein

ABSTRACT

In order to create a strategy for the development of climate scenarios for use in impact assessment, potential techniques of development were reviewed and the information needs of potential users assessed. Available techniques were assessed through literature reviews and consultations with scenario development experts. Techniques were divided into ten modules, groups of techniques with similar methodologies, input requirements and output formats. Three modules involve approaches which model atmospheric processes, four concern analysis of past climate records, and three concentrate on methods for linking the other two. Each module can provide a scientifically well-founded piece of needed information, and a series of modules used together will produce the scenario. User needs were assessed in consultation with selected individuals who had experience in the use of scenarios. The major needs were revealed to be for general descriptive statistics of the major climatic elements, for information about climatic anomalies, notably drought, for statistics on the frequency and probability of events exceeding particular thresholds, and for general information about storminess. The results of the two sets of assessments are combined to provide a scenario development strategy. An iterative approach is recommended. Project areas incorporating both scenario development efforts and fundamental research are identified for the first three iterations.

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The students in the Seminar served as witting or unwitting guinea pigs for the testing of many ideas. Their invaluable role is acknowledged.

Numerous people, herein anonymous, responded to our questions of the scenario users. Their time, effort, and insight is duly acknowledged with thanks.

SECTION 1

GOAL AND OBJECTIVES

The overall mission of the U.S. Environmental Protection Agency (EPA) Global Climate Change Research Plan (Environmental Protection Agency, 1989) is the assessment of the potential impacts of climate change on the environment, with particular emphasis on regional impacts in ecology, water resources, and air quality. A key element within this mission is the development of climate scenarios oriented toward the needs of those assessing these impacts.

The goal for the current report is to:

provide recommendations and priorities for the development of techniques to produce impact oriented scenarios.

To meet this goal, the specific objectives are as follows:

a) Identify all techniques potentially available for the development of scenarios;
b) Identify user needs in areas where EPA is responsible for impact assessment;
c) Assess appropriate techniques for impact-oriented scenario development, including assessment of current knowledge, level of effort needed, speed of potential development, needs of users, and suitability for transformation into routine scenario production techniques;
d) Provide recommendations to EPA for the priorities for research, development, and production of impact-oriented climate scenarios.

A scenario is defined as:

A suite of possible future climates, developed by using sound scientific principles, each being internally consistent, but none having a specific probability of occurrence attached.

This general definition applies to all elements of climate for any time in the future. However, to meet the EPA mission there are several requirements of scenarios:

- They must be tailored to user needs.
  Any scenarios produced must emphasize those climatic elements, time scales, space scales, and geographic regions of prime concern to those undertaking the impact assessment. In practical but general terms, **regional scenarios**, covering a specific geographical region, must be produced.

- They must be scientifically sound.
  The current state of the science is such that many assumptions must be included when any projection of future climate is made. Established scientific principles should be used whenever possible, so that the assumptions are reduced to a minimum. All assumptions should be tested using accepted scientific methods, their influence on the results evaluated, and their presence made explicit in any documentation associated with the scenario.

- They must be internally consistent.
  Any scenario which is produced must be based on the established physical, chemical and biological laws controlling geospheric processes. Thus a scenario must not contravene these laws, which control not only the theoretical limits of variability of a single climatic element, but also the relationships between two or more elements and their temporal and spatial variability.

- They must provide a range of future conditions.
  A scenario is regarded here as a single estimate of the future climatic conditions. Since no deterministic forecast of the future is possible and no single scenario can be regarded as the "best estimate" of the future, a set of scenarios creating a range of possible futures must be produced. These may be developed from variations of the assumptions within a single scenario development method or by the use of alternative methods.

The concern that climate change may have an impact on human affairs is rather recent and there is a relatively small, but rapidly increasing, body of experience in development of scenarios. Some scenarios (e.g., Jager and Kellogg, 1983; Wigley et al., 1986) have been created primarily to assist in understanding climatic change, but the majority have been oriented

towards the assessment of potential impacts. These include some general purpose scenarios designed to treat a variety of impacts (e.g., Smith and Tirpak, 1988; Pearman, 1988) and some more closely tailored to specific ones (e.g. Palutikof et al., 1984; Cohen and Allsopp, 1988; Gleick, 1987; Linder et al., 1987). A variety of techniques have been used, and Lamb (1987) has emphasized the wide range of techniques potentially available. However, no comprehensive review of possible approaches has included assessment of the strengths, weaknesses, and suitability for particular tasks of the various potential techniques. Such a review must be undertaken if appropriate, efficient, and effective scenarios are to be developed.

The users of these scenarios are those responsible for assessing the potential impacts of future climate changes. They also have little experience. Assessments are commonly undertaken using some form of model where statistics derived for the present climate are the input. This information is combined with information about the impact, and manipulated in various ways to yield an output relating climate variations to the specific impact. However, it is often difficult to disaggregate the model to identify those climatic elements and modes of variation which are most important, and therefore those elements whose emphasis in future scenarios is most important. Thus users have had varying degrees of success with the presently available scenarios. The initial experience, however, provides insights into the real information needs of users, and which is assessed here as an important element in the production of user-oriented scenarios.

Combining both the user needs and the scenario development possibilities, potentially fruitful lines of research into methods of scenario development can be identified. By including consideration of the development effort required, probability of success, and the potential for transforming the method from a research tool to an operational technique, it is possible to develop priorities and recommendations for scenario research. This constitutes the final section of this report, discussed in detail in Section 5 and reviewed as recommendation in Section 2.

This review provides a theoretical framework upon which practical experience of scenario development must be built. Current knowledge, along with the value of the experience likely to accrue from creating and using scenarios, dictates that an iterative approach to development be used (Figure 1). Scenarios are developed by climatologists in cooperation with users and tested by those users. Refinements can be incorporated as a result of both the user evaluation and the ongoing scenario research. Over several iterations scientifically sound, readily usable, and clearly documented scenarios can be produced for routine use in impact assessment.

FIGURE 1. The iterative approach to scenario development.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

This project assessed the information needs of potential users of climate scenarios, the methods available to develop scenarios, and strategies for research to develop scientifically credible impact-oriented scenarios.

User needs were ascertained through consultation with people having some experience with scenario use. The major needs are:

- Simple descriptive statistics for individual climatic elements.
- Climate anomaly information, especially concerning drought.
- Information about the frequency and probability of occurrence of various threshold values.
- Synoptic information, especially concerning storms.

Potential scenario development methods were identified through literature reviews and consultations with people having experience in scenario development. It was recognized that currently available scenarios are primitive and may be misleading, but that techniques are already available to produce more scientifically sound ones.

From these investigations, it is recommended that **a modular approach to scenario development be adopted**. Each module consists of a set of related analysis techniques which are themselves well established and tested, and which can be used to provide pieces of information required for scenarios. Linkage and combination of modules allows the development of a complete scenario.

Ten modules were identified. Three involve process models which use the laws of chemistry and physics to provide understanding of the processes acting to control climate, and thus can be used directly to investigate climatic changes resulting from the greenhouse effect. Included with these are the General Circulation Models which provide the main basis for development of scenarios. Four modules incorporate empirical techniques for scenario development, which use the records of past climatic conditions to provide

indications of the nature of climatic variations on the time and space scales needed for most impact assessments. The final three modules are linkage techniques designed to allow combination of the other modules to provide the required scenarios.

The techniques in each of these modules are at various stages of development. Some can be used directly for scenario production while for others a major research effort is needed before they can be used. For almost all of them, their suitability as scenario production techniques has yet to be tested.

Because of the various levels of development of the modules, and given the overall lack of experience with scenario development, it is recommended that **an iterative approach to scenario development be adopted**. For each phase a set of scenarios are produced and used for the assessment of a particular impact. Thereafter the scenario is assessed for its scientific credibility and its value for impact assessment. Appropriate modifications and refinements are made and a new scenario produced to start the next iteration.

Three phases of iteration are recommended here, covering the short-term (1 - 2 years), the medium-term (3-4 years), and the long-term (more than 4 years). Within each phase, three types of projects are recommended:

- Scenario development
  The actual production of scenarios which can be provided to the users for impact assessment.

- Module research
  Investigations aimed at refining the techniques within modules to produce more soundly based scenarios.

- Ancillary activities
  Projects designed to ensure that any scenarios produced are responsive to user needs and can be routinely and easily used in impact assessment.

Details of the research strategy and specific projects are given in Section 5.

SECTION 3

SCENARIO DEVELOPMENT METHODS

The assessment of potential scenario development methods commenced with the assertion that any and all techniques of climatological analysis were candidates as scenario development methods. The first stage of the project started with a literature review to identify these techniques. This was followed by meetings with "scenario development experts", who assisted in refining the ideas and concepts generated during the literature review. These meetings were undertaken within the framework of a seminar on scenario development, an approach which proved highly successful (see Appendix A). This stage of the assessment yielded about 60 techniques which had potential application to scenario development. This large number necessitated the development of a method to synthesize the individual techniques into a manageable number of groups.

This synthesis was achieved by developing the concept of the modular approach to scenario development. A module is a group of techniques which have similar input requirements and provide similar types of output information. For the needs of a particular impact-oriented scenario, several modules are combined to provide the required climate information (Figure 2).

Three basic types of modules were identified: Process Models, Empirical Methods and Linkage Techniques. The first two arise because of the fundamental division in the type of climatic information available for scenario production (Lamb, 1987). The process models attempt to use the underlying physical laws of atmospheric processes to deduce climate under changed conditions. The empirical approaches use the records of past climate to indicate possible future conditions. Both approaches have strengths and weaknesses (Table 1). A consensus is emerging (Gates, 1985) that process models must form the basis of any scenario because they provide the only means for explicitly estimating climate in changed atmospheric conditions. At present, however, such models cannot provide the spatial and temporal detail needed for the provision of user-oriented scenarios. Hence they must be linked to empirical methods if useful scenarios are to be produced. Although the importance of this linkage may decrease as the process models become more sophisticated, detailed, and reliable, it is clear that they will be needed well into the foreseeable future. Methods of establishing these links provide the third major group of scenario modules.

FIGURE 2. The modular approach to scenario development.

TABLE 1: THE MAJOR STRENGTHS AND WEAKNESSES OF THE PROCESS AND EMPIRICAL APPROACHES TO SCENARIO DEVELOPMENT

	STRENGTH	WEAKNESS
PROCESS MODELS		
	Explicitly incorporate many atmospheric processes	Coarse temporal and spatial resolution
	Directly include changed atmospheric composition	Few elements estimated with any confidence
EMPIRICAL METHODS		
	Provide great temporal and spatial resolution for many regions	Cannot readily consider changed atmospheric composition
	Many elements available	Processes deduced only by inference

In developing the concept of the modules no attempt was made to ensure that a particular task could be performed by a technique in one and only one module. In addition, some techniques may include features appropriate to several modules. Nevertheless, ten distinct modules, each with various subdivisions, were identified (Table 2). These all use existing analysis techniques although their level of development may vary. It can be anticipated that entirely new methods of analysis will be revealed as experience with scenario development increases.

3.1 *PROCESS MODELS*

The process models strive to use the laws governing atmospheric processes to understand the present conditions and estimate future ones when boundary conditions are changed. There are numerous possible approaches to process modeling. The major division adopted here is based on spatial scale (Table 3). Different modeling techniques, having different input requirements and output products, are used for each scale (Manabe,

1985). Each module is labelled with a general spatial scale, but an associated temporal scale is equally implied.

Process models include both "physical" and "chemical" models. The former are emphasized here, being more directly related to the elements normally regarded as climatic. Further, many of the chemical models are designed for air quality assessments, and thus people using them constitute one group of users for whom scenarios must be designed. Nevertheless, chemical activity in the atmosphere can have an major influence on the climate itself (Ramanathan et al., 1985), and there are important links between chemistry and climate at all scales (Penner et al., 1988), so chemical models are considered explicitly in several of the following sections.

To a great extent, EPA's mission in the climate program includes development of chemical models but not physical ones. Thus it is assumed that the primary interest in physical process models is with their outputs, rather than with their development directly. For the physical models this concern includes maintaining awareness of the state of model development, identifying and fostering research which provides outputs in formats suitable for user-oriented scenario creation, identifying opportunities for model use, and using the models in scenario development. The same approach is adopted for the chemical models, although here there is the opportunity for closer interaction with the model building community within EPA.

GLOBAL MODELS

The major emphasis of the process-oriented global models is the understanding of the whole climate system. There are numerous types, ranging from relatively simple zero-dimensional energy balance models, through one- or two-dimensional radiative-convective models, to the full three-dimensional general circulation models (Henderson-Sellers and McGuffie, 1987). In recent years almost all attention has focussed on the general circulation models (GCMs) which have become synonymous with "climate models". Indeed, they are at present the only type of global model which provides output having the potential for use in scenario development.

General Circulation Models are being developed by several groups (Schlesinger and Mitchell, 1985). Although the details of model development vary tremendously between groups, the basic approach is to solve the equations of atmospheric motion for several atmospheric pressure levels at a series of regular grid points covering the earth. The grid resolution ranges anywhere from 4° lat. x 5° long. to 8° lat. x 10° long. With this coarse resolution it is possible to integrate the circulation of the model atmosphere

TABLE 2: THE POTENTIAL SCENARIO DEVELOPMENT MODULES

PROCESS MODELS	EMPIRICAL METHODS
Global Models	**Analogue Techniques**
General Circulation Models	Instrumental Analogues
Global Chemical Models	Proxy Analogues
	Spatial Shifts
Regional Models	**Circulation Analysis**
Numerical Weather Prediction Models	Circulation Indices
Regional Climate Models	Teleconnections
Regional Chemistry Models	
Local Models	**Climatological Statistics**
Mesoscale meteorological Models	Mean Statistics
Urban Chemistry Models	Event Statistics
Surface Boundary Models	Temporal Statistics
	Synoptic Analyses
	Statistical Synoptics
	Spatial Synoptics

LINKAGE TECHNIQUES

Adjustment Methods
- Statistical Adjustment
- Spatial Adjustment

Transfer Function Methods
- Statistical Transfers
- Process Transfers

Synthetic Methods

TABLE 3: PROCESS MODEL INPUT REQUIREMENTS AND OUTPUT PRODUCTS

	INPUT		OUTPUT	
	Scale	Elements	Scale	Elements
Global Models				
General Circulation	Global Monthly	Actual/modeled climatological data	Grid-cell Monthly	Temp, precip, circulation, etc. Means and variance
Global Chemical	Global Monthly	Source/sink strengths Various species	Broad area Monthly	Atmospheric concentrations Means
Regional Models				
Numerical Weather	Regional Daily	Analyzed synoptic data	Synoptic Daily	Temp, precip, circulation, etc. Weather forecasts
Regional Climate	Regional Daily	Analyzed synoptic data	Synoptic Daily	Temp, precip, etc. Simulated weather
Regional Chemistry	Regional Daily	Actual/synthetic weather stream	Synoptic Daily	Chemical composition, Air quality
Local Models				
Mesoscale meteorological	Local Hourly	Weather observations Surface characteristics	Local Hourly	Temp, precip, severe weather Short-range weather forecasts
Urban Chemistry	Local Hourly	Emission strength/type Surface characteristics	Local Hourly	Air quality
Surface Boundary	Local Hourly	Weather observations Surface characteristics	Local Hourly	Energy & materials budgets Fluxes and concentrations

for the long periods of time required to produce climatic statistics. Since the atmospheric composition is included as part of the model structure, it is possible to arbitrarily change the model atmosphere composition. Most experiments, after a control run using present conditions, assess equilibrium conditions when the effective carbon dioxide concentration (which takes into account all of the radiatively active trace gases) is doubled or quadrupled (e.g. Manabe and Stouffer, 1988). These experiments commonly involve an instantaneous change in composition, but transient runs (Hansen et al., 1988), which allow the atmospheric composition to change gradually at a realistic rate, are being developed to produce estimates of the evolution of climatic changes (Bryan et al., 1982).

The published results from these experiments tend to emphasize surface temperature and precipitation patterns, or variables such as soil moisture which are directly derived from them (Kellogg and Zhao, 1988; Abramopoulos et al., 1988). However, other elements, such as radiation, albedo, cloudiness, geopotential height, and ice cover, are also calculated. User needs for these products must be clearly identified and the modeling community encouraged to analyze, or make available for analysis, those products which are of potential use in impact assessment.

The GCMs have become the main vehicle for the assessment of future climate. They are not without their drawbacks. The various models are in reasonably close agreement about globally averaged temperature changes but they vary tremendously once conditions over smaller areas, or elements other than temperature, are assessed (Grotch, 1988). Hence there is uncertainty as to appropriate values to use when creating a regional scenario based on GCM results. Indeed, GCMs could be inadequate as scenario development modules if the climate system behaves differently than the models predict. In addition, the spatial and temporal resolution is constrained by the model formulation and by practical considerations of computation facilities. The finest resolution possible may not be sufficient to provide the detail needed by the user of a scenario.

Great advances can be anticipated within the next 5 - 10 years in the reliability of regional values produced by GCMs, stemming from the great amount of research, investigating better parameterization of the climatic processes, better incorporation of the effects of the surface boundary, especially oceanic processes, and better specification of the role of clouds. It is much less certain, however, that the temporal and spatial scales of analysis can be refined in the near future, so that other methods of analysis will need to be incorporated for scenario production purposes.

Thus it must be emphasized that this module should not be used on its own to produce a scenario. The uncertainties, assumptions and parameterizations, and spatial and temporal smoothing, within the models, readily acknowledged by all modelers, ensure that the direct use of a model is likely to create misleading results at best. Hence the GCM's results must be regarded as starting points for scenario development, not as end points.

Global Chemical Models are required to provide chemical information both for air pollution studies and for linking to GCMs. Most GCMs pay scant attention to chemical activity in the atmosphere, although as the physical elements of climate change so will the rate, and possibly type, of chemical reactions which will, in turn affect the physical elements. Thus linkages between global chemical models and GCMs are likely to provide better estimates of future climate. The global chemical models also provide the background chemistry used by the regionally oriented chemical models which are of concern in scenario development. Although some one-dimensional (Thompson and Cicerone, 1982; Bruhl and Crutzen, 1988) and two-dimensional (Wuebbles and Edmonds, 1988) models are available, the global chemical models are not as well developed as are the GCMs.

Consequently, although the regional chemical models are of most immediate interest, the development of global models is to be encouraged as providing necessary background information.

REGIONAL MODELS

The regional process models are designed to cover an area roughly corresponding to a few GCM grid-cells and to indicate conditions on a daily time scale. At this scale the emphasis until now has been on weather forecasting rather than climate. Consequently it is necessary to explore the potential for transforming the models based on short-term events into climatic models.

Numerical Weather Prediction Models have been the subject of intense study for many years (Richardson, 1922; Haltiner, 1971), and is the focus of much research within many weather forecasting organizations. These models (e.g., Gerrity, 1976; Phillips, 1979) commonly provide information about surface pressure, 1000-500 mb thickness, precipitation totals, vertical motions and heights, and wind, humidity and temperature on constant pressure surfaces, with a grid spacing of about 100 x 100 km. The models provide forecasts every 6h for up to two days ahead.

These models more realistically incorporate the structure of the atmosphere than do the GCMs, but they are designed as short-term forecasting tools and are not formulated to address climate change questions. Nevertheless, they provide highly detailed output of the type required for impact assessment. Consequently, the potential for modifying them or combining them with other methods to provide climate information must be explored.

Regional Climate Models are not well developed, but one major attempt to produce a regional climate model has been made by Dickinson et al. (1988). They used GCM outputs to drive a mesoscale meteorological model to provide a regional model for the Great Basin of the western United States. The results were encouraging, producing a simulation of precipitation distributions for a single storm event in a changed climate which appeared reasonably realistic. This work is in an embryonic state. Numerous problems remain. At present the linkage between models is only one way: i.e. the GCM affects the mesoscale model but not the reverse. Further, it is not clear how these event-based models can be used to provide a climatology containing means and variance of the climate elements. It is also extremely difficult to design validation techniques for this type of event model.

Nevertheless, it is clear that development of regional models is possible and should be encouraged. A variety of models should be tested, various methods of incorporating surface effects investigated, and two way links developed. Indeed, linkage between models of various scales is vital. A substantial amount of work is needed before these models can become scenario development tools.

Regional Chemical Models are available in several forms. Many, such as the Regional Acid Deposition Model (RADM) and the Regional Oxidant Model (ROM), were developed by or in close cooperation with EPA (Stockwell and Tang, 1987). These models are three-dimensional with a spatial domain covering about a third of the United States and a time domain from about three days to two weeks. They include a variety of complex gas-phase chemical transports and transformations. These models are driven by a "weather stream" provided by a numerical weather model (Selby, 1987; van Dop et al., 1987), and are "event based", designed primarily for regional air quality assessments and the investigation of air pollution episodes. While pollution may in reality interact directly with the climate, so that links between the chemical and meteorological models are desirable, these links are not now possible. It is most convenient to regard the regional chemical models as application modules for a particular group of impact assessors.

If these models are to be used to assess potential air quality under a changed climate a suitable future weather stream must be developed. Thus the research needs are primarily those associated with the regional climate models, with additional investigations of linkage methods for the physical and chemical components. Again this is fundamental work to be fostered, not a well-established scenario development technique.

LOCAL MODELS

Local models are defined here as models with time scales of minutes to hours and space scales of 1 - 100 km. They thus embrace both the mesoscale and microscale meteorological domains. The models are concerned with individual weather or air pollution events over areas on the space scale of field or a city. Close attention is paid to the links between the atmosphere and the underlying surface. In general, the models in this module serve as links between the broad scale climate and the detailed information required by many users (e.g., Stern and Coe, 1982). Indeed, in many cases these models produce the type of information needed by users to drive application models and thus to assess impacts.

Mesoscale Meteorological Models are currently receiving a great deal of attention, and many techniques are being developed (Pielke, 1984). Although these models use approaches that are similar to the regional numeric models, the spatial and temporal resolution is much finer, and the size of the domain is only a fraction of that considered in the regional models (Anthes et al., 1987). Most investigations have been for particular types of situations, such as tropical squall line features by (Nicholls and Weissbluth, 1988), or tornadoes and lake effect blizzards (Perkey and Maddox, 1985). No single model with wide-ranging applicability on this scale has yet emerged, although recently there have been attempts to provide parsimonious models (Wang and Warner, 1988) and to incorporate scale interactions (Von Tuyl and Errico, 1989). Thus some general modeling problems are being considered which may lead to benefits for scenario development. At present, direct inclusion of mesoscale meteorological models is not possible, given their emphasis on highly specific situations and their extensive computational needs. Further investigations of scale linkages and model generalization are to be encouraged, enhancing the long-term prospects of their incorporation into scenarios.

Urban Chemistry Models are designed to assess the species, reactions and concentrations occurring within a local area in response to the specific local situation (Chameides et al., 1988; Trainer et al., 1987). The climate variables they use, including the diurnal temperature profile, humidity,

and vertical mixing depth, are prescribed, and no interaction between the physical and chemical effects are incorporated. The models must be regarded as users of climate information rather than modules for scenario development. At present input values must come from other scenario modules which provide highly localized and detailed information, notably the physically-oriented surface boundary models. However, if realistic assessments of surface processes and of urban air quality are to be made, local models incorporating both physical and chemical interactions must be developed. Research to produce such models must be stimulated.

Surface Boundary Models are physical models whose main emphasis is the specification and linkage of the near surface atmosphere to the surface and the underlying medium. They are treated together here because they have a common role in providing information needed to assess impacts. Many of the models, in fact, have been created for the purposes of assessing specific impacts (Rosenberg et al, 1983). A great variety of techniques have been developed, but there are three main lines of approach: turbulent exchange within the planetary boundary layer; surface energy and materials budgets; and urban climate.

Models of turbulent exchange within the planetary boundary layer (e.g., Gutman and Apterman, 1987; Mahfouf et al., 1987) are of particular concern for air quality and atmospheric dispersion studies, and are relatively well developed. A major requirement for scenario development is to establish links which allow these small-scale models to connect with the larger scale ones. Here studies such as those of Pan and Mahrt (1987), linking boundary layer development and general surface hydrology, Sud and Smith's (1985) investigation of the relationship between surface roughness and the overlying circulation, and the surface flux analyses of McCumber and Pielke (1981) suggest possible lines of approach.

Many studies of surface energy and materials budgets have been connected directly to information production for agriculture, ecology and forestry through variables such as evapotranspiration and the sensible heat flux (e.g., Tajchman, 1972). Early studies treated relatively flat surfaces, but increasing attention has been paid to the influence of topography, both for the energy fluxes (Brutsaert and Kustas, 1985) and for links to low-level circulation (e.g., Bader and McKee, 1985; Mason and King, 1984). There have also been investigations of the relationship between surface type and the overlying circulation (e.g., Anthes, 1984) and of the influence of surface fluxes on GCM outputs (Delworth and Manabe, 1988).

One area receiving special attention is the urban climate (Oke, 1982). A major recent emphasis has been on the temporal changes as urbanization increases (e.g., Adebayo, 1987; Balling and Brazel, 1987). A recent EPA-sponsored review (American Meteorological Society, 1987) identified many of the problems and opportunities for research within urban areas, with special reference to urban air quality problems.

The techniques in this module provide vital components in scenario development, providing the link between the broader scale models which can explicitly incorporate climate changes and the application models needed to assess impacts. It is likely that individual techniques will continue to address specific aspects of the boundary layer, because it is proving extremely difficult to produce a detailed model with general applicability. A major need, however, is to foster research directed towards incorporating both physics and chemistry into the various models at this scale. Further, the state of development of these surface boundary layer models must be monitored, so that scenario development schemes using linked modules can incorporate them in the most appropriate ways.

3.2 *EMPIRICAL METHODS*

Within the empirical techniques category are analyses of past conditions, whether the instrumental record of the past few decades, historical sources for the past few centuries, or the paleoclimatic reconstructions of past millennia. The strength of these approaches is that many of the techniques are well established and can provide a great amount of detail derived from actual, known occurrences. The prime drawbacks are that the physical causes of future climate conditions may be different from those of the past, and so the future conditions may be outside the past range of observed situations. The modules and their major subdivisions are summarized in Table 4.

ANALOGUE TECHNIQUES

This module consists of scenarios developed by direct analogy with actual past and present climates. Two lines of approach are available: use of historical information to identify past climate patterns, and use of geographical techniques to suggest shifts in climate belts as global climate changes.

TABLE 4: EMPIRICAL METHODS INPUT REQUIREMENTS AND OUTPUT PRODUCTS

	INPUT		OUTPUT	
	Scale	Elements	Scale	Elements
Analogue Techniques				
Instrumental	Local/regional Daily/monthly	Any measured element	Local/regional Monthly/seasonal	Same as input average values
Proxy	Regional/national Monthly/decadal	Any obtainable from proxy data	Regional/national Annual/decadal	Same as input average values
Spatial Shifts	Regional Monthly	Any measured element	Local Monthly	Same as input average values
Circulation Analysis				
Circulation indices	Synoptic Daily	Analyzed synoptic data	Synoptic daily/monthly	Circulation statistics means, variance etc.
Teleconnections	Synoptic Monthly	Analyzed synoptic data	Synoptic seasonal	Relation between certain areas average values
Climatological Statistics				
Mean Statistics	Any space/time	Any elements	Any	Statistical summaries means and variances
Event Statistics	Any space/time	Any elements	Any	Statistical summaries probabilities, frequencies
Temporal Statistics	Any space/time	Any elements time sequence data	Any	Same as input trends, frequencies, etc.
Synoptic Analyses				
Statistical synoptics	Synoptic Daily	Analyzed synoptic data	Local	Weather types probabilities/frequencies
Spatial synoptics	Synoptic Daily	Analyzed synoptic data	Regional	Regional definitions spatial variability

Instrumental Analogues were used to produce some of the earliest scenarios. Since the variations during the observational period were rather minor, at least when compared to future changes suggested by GCMs, several approaches have been used. One is to take a series of "extreme" years and assess their circulation patterns and surface climate. A major drawback is that a single year is a transitory phenomenon, with the atmosphere and ocean having no chance to establish equilibrium in the new conditions (Jager and Kellogg, 1983). Hence an alternative approach used "warm" or "cold" decades. Even a decade is short from an equilibrium standpoint, while the climatic variations have been minor. Hence this approach as a potential technique has limited application. However, examinations of the circulation patterns in these recent extreme periods have the potential to provide some degree of validation for other approaches.

Proxy Analogues make use of proxy information, either derived from recorded historical events or deduced from paleoclimatic investigations, to develop scenarios covering a wide range of past climatic conditions. For example Parry (1975) assessed the climate during the Little Ice Age from records of land use and settlement in an agriculturally marginal area in Scotland. This approach, extended to other marginal areas (Parry and Carter, 1985), has proved highly successful in suggesting direct links between climate variations and their impacts. On a longer time-scale paleoclimatic investigations provide information for the last few thousand years (Webb and Wigley, 1985). In many cases ecological indicators have been used (e.g., Jacobson et al, 1987). These provide direct links between climate and impacts. This has served to indicate not only changes in ecosystem location (Stahle and Hehr, 1984; Webb, 1987) but also changes in species composition (Davis, 1981). Other paleoclimatic investigations, including ice core analysis (Barnola et al., 1987) and glaciological research (Budyko and Izrael, 1987) have given more direct measures of past climate itself, including some at times when the atmospheric composition approached that of the "greenhouse effect" (Budyko, 1989). Thus there is a double role for proxy analogue scenarios. First they provide empirical evidence of past conditions, allowing testing of the credibility of the results of scenarios developed by other methods. That role has already started in the comparison of paleoclimatic results with those obtained from GCMs (COHMAP, 1988). Second, they allow establishment of links between climate and its impacts and the identification of the significant climatic variables needing to be analyzed.

Spatial shifts are techniques which specify future climate conditions at a place in terms of the current conditions at another place. Thus as statements such as "The climate of (New York City) will become like that of

(Richmond, VA)" provides a succinct, readily understandable summary of climatic change, and one that is often used in the popular media. The most common approach (Smith and Tirpak, 1988) is to take the results of a GCM run as representing the new climate at a particular spot. It is then a simple matter to search the current climate record for locations which have at present the same characteristics as the postulated future climate at that spot. The skill is to choose the appropriate place. If the scenario is couched in terms of monthly values only, there will be a range of candidate locations having, more or less, the appropriate characteristics. The more detail that is provided by the scenario, the smaller the range and the less likely an exact match. Ultimately, however, the choice of analogous station must be subjective. Thus it is unlikely that this technique can provide the quantitative information required for many impact assessments. Nevertheless, it is appropriate to pursue it as a means of summarizing results from other methods because it is so simply stated and evocative of future conditions.

CIRCULATION ANALYSES

The close relationship between the upper airflow and surface weather is used extensively in weather forecasting (e.g., Gilman, 1985). Consequently the climate of a region is greatly influenced by the frequency of various types of circulation patterns aloft, and as their frequency changes, so will the surface climate. Namias (1983), for example, demonstrated the close connection between flow patterns and drought in the United States. Hence techniques which specify and analyze circulation patterns provide a module for scenario development. Indeed, because global models are primarily circulation based, it is possible that close connections between process models and circulation analysis can be established to provide a fruitful scenario development approach.

Circulation Indices of various types have been developed to characterize the upper airflow in forms which foster connections with surface conditions. For mid-latitude weather forecasting the flow is summarized by the number and position of the planetary waves (Wallace and Hobbs, 1977). This approach has not been extensively explored for surface climatology development, but may provide valuable information. For climatological work, it is more common to use indices which reflect pressure differences between various locations, such as the Southern Oscillation Index (Ropelewski and Jones, 1987), the Pacific-North America index (Lamb and Peppler, 1987), and the North Atlantic Oscillation (Moses et al., 1987). Each of these has been used to explore the nature and causes of climate variability over large regions. Yarnal and Leathers (1988) have indicated that they can be used to explore small-scale climatic variations, although methods of linking scales are

not well established. For scenario development, therefore, the broad-scale circulation indices hold great promise, but methods will have to be developed to link them to local circulation patterns and local climate.

Teleconnections are a tool used to investigate the climatic relationships between discrete areas. For certain locations elements such as pressure, temperature, and precipitation show simultaneous correlations despite their apparent disconnectedness in space (Angstrom, 1935; Yarnal and Kiladis, 1985). The connections are identified by statistical analysis, and the underlying physical mechanisms postulated but not proved. A number of teleconnection "centers" have been identified (e.g. Wallace and Gutzler, 1981; Mo and Livezey, 1986). The best known, and the one seemingly with the strongest influence on global climate variability, is the Southern Oscillation. This pressure oscillation forces climate variations throughout the tropics (Yarnal and Kiladis, 1985; Rogers, 1988) and into mid-latitudes (e.g., Hamilton and Garcia, 1986; Ropelewski and Halpert, 1987). Teleconnections can play two roles in scenario development. First, the established relationships between regions provide another piece of information available to validate process models, since teleconnections should be an integral part of model outputs if the specification of global circulation is to be regarded as valid (Palmer and Zhaobo, 1985). Second, they provide a means of establishing and checking the "external" consistency of scenarios. When scenarios for different areas are produced, they should retain any known teleconnection patterns unless sound contrary evidence, based on the nature of the changed climate system, can be provided. Teleconnections can be vital for impact assessment. For example, Rauner (1980) demonstrated the difference in potential impact on the global grain trade resulting from different teleconnections patterns in the various grain-producing regions of the world.

CLIMATOLOGICAL STATISTICS

Within this category is a great range of potential approaches, combined here because they all emphasize the pure statistical manipulation of observational data. While some consideration may be given to atmospheric processes and climatology, the focus in these methods is on the statistics, not the processes. The techniques considered here use the observational climate record. Although extrapolation may suggest future conditions, this assumes continuation of present conditions or trends, which may not be valid. The methods can be extended to asses model outputs, a subject which has received little attention beyond the intercomparisons provided by Grotch (1988). There are thus two roles for the climatological statistics module: validation of model outputs for the current conditions; and provision of detail for incorporation into scenarios of future climate.

There has been a tremendous amount of statistical analysis of observational climatic data. Nevertheless, there are still fundamental statistical questions to be addressed (Switzer, 1988). These can be summarized as:

1) analysis techniques to use when the main concern is for a non-stationary record;
2) methods for spatial analysis as rigorous as those for temporal analysis, including analyses where many elements, which may have different spatial distributions, are involved;
3) the influence of the non-uniform distribution of observational sites on analysis techniques;
4) the development of methods of linking observations, and performing analyses, on various temporal and spatial scales.

These constitute overarching research needs, having an influence on all of the techniques considered below.

Because of the great amount of previous work and the great range of techniques which have been developed, this module is divided into three broad, and overlapping, categories based on the type of output the techniques most commonly produce. These categories are labelled, for convenience: Means statistics, Event statistics, and Temporal statistics.

Mean statistics, including consideration of both means and variance, can be developed in various ways, for various elements and with various time and space scales. In this area a great many techniques have been developed, and they are here reviewed only briefly.

The most basic approach is to use **univariate descriptive statistics** for a single climate element, or elements combined to produce a single variable. These methods are frequently used in exploratory data analysis to deduce patterns requiring more sophisticated treatment. A typical example is the work of Mearns et al. (1984), who explored the relationship between seasonal temperature variability and seasonal average temperature. Similarly Stockton and Boggess (1979) used the approach, linearly relating temperature, precipitation, and streamflow, in a pioneering attempt to provide hydrologically related scenarios, an attempt subsequently refined by Nemec and Schaake (1982). Recently Sharon (1989) has developed tests with the power to assess the significance of the relationships developed.

A logical extension of this approach is to use multivariate statistical methods for analysis of several elements in combination, and these have been used for a wide variety of purposes (Ikeda et al., 1980). Many investigations emphasize **principal component analysis** (Richman, 1986). Surface-based data can be used to suggest regional divisions and provide a

starting point for an explanation of patterns. Eder et al. (1987), for example, identified spatially and temporally concurrent drought regions in the southeastern United States, information leading to a search for causal processes. Stidd (1967), on the other hand, analyzed Nevada precipitation to provide process-oriented information about the causes of the different seasonal regimes. Some investigations explicitly incorporate both upper air and surface conditions (e.g., Kutzbach, 1969) and may have an important role to play in establishing links between GCM outputs and detailed surface climate.

While recent research attention has concentrated on exploring and extending these multivariate methods, numerous other techniques are available to deal with particular circumstances and needs. In some cases, for example, it is more appropriate to use **cluster analysis** for the development of regional divisions for specific elements (e.g., Nicholson, 1986). When temporal patterns, notably the diurnal and seasonal cycles, are the main concern, **harmonic analysis** has proved useful as a statistical analysis technique, providing the basis for physical understanding and the specification of regional differences (e.g., Easterling and Robinson, 1985; Horn and Bryson, 1961). In situations where the assumption of a near-normal distribution of the observations cannot be supported **non-parametric statistics** have been used. Thus Seilkop and Finkelstein (1987) used Kriging techniques to explore the regional distribution of atmospheric deposition in the eastern U.S., and Robinson and Fesperman (1987) used rank-order statistics to identify mesoscale areas prone to simultaneous precipitation deficits. All of these methods are usually regarded as the first step in an analysis where the main concern has been to identify the processes controlling the element.

Event statistics, such as the frequency and magnitude of extreme floods, the probable length of a dry period, the number of consecutive days with high temperatures, or the likely sequence of weather situations, are needed by many application models. To address such questions three general lines of approach are possible: extreme value analysis, probability functions, and time series methods.

Techniques of **extreme value analysis** have been extensively explored (e.g., Carter and Challenor, 1981; Tiago de Oliveira, 1986), with particular emphasis on wind and precipitation extremes. For the former the Weibull distribution is commonly used (Conradsen and Nielson, 1984), although the limitations of the method are well known (Tuller and Brett, 1984). For hydrologic applications a broader range of distributions has been examined, both for precipitation directly (Revfeim, 1983) and for the hydrologic

consequences of extreme events (Ashkar and Rouselle, 1983; Ely and Peters, 1984). Wilks (1989) demonstrated the applicability of a modified Weibull distribution, not only for ascertaining "record breaking" events, but also as a means of establishing the frequency of occurrence of events above (or below) a "threshold" of concern for a particular impact. All of the distributions, however, assume stationarity in the observational record. Any consideration of climatic change contravenes this constraint, and methods must be developed to explicitly incorporate non-stationarity if realistic scenarios are to be produced. Nevertheless, the importance of considering future extreme events has been demonstrated (Wigley,1985), and there are opportunities to use extreme value analysis alone or in combination with other methods such as circulation analysis (Parthasarathy et al., 1987) or synoptic analysis (Maddox et al., 1979) to provide scenario information.

There is also a long tradition of **probability analysis** within the climatological literature (e.g., Jenkinson, 1954; U.S. Weather Bureau, 1961). Although there has been consideration of several climate elements, such as synoptic events (Ratcliffe et al., 1978), freeze or thaw dates (e.g., Schmidlin et al., 1987), and thunderstorm frequency (Changnon, 1988a, 1988b; Robinson and Easterling, 1988), the majority of investigations have involved precipitation (e.g., Berger and Goossens, 1983; Dennett et al., 1983; Guzman and Torrez, 1985). Here there has been concern both for the appropriate distribution to use (Thom, 1958) and for the type of information needed (Jackson, 1986). Some investigations have also provided pointers for linking probability approaches with others to produce more soundly based scenarios. Sharon and Kutiel (1986) divided precipitation into types which allows the development of relationships with circulation patterns, and Tyson (1984) explicitly explored the links between precipitation probability and circulation. These approaches must be explored further to establish the scale linkages likely to be needed in the development of scenarios.

Temporal Statistics refer to those techniques whose main focus is the variation of climatic elements over time, with the various techniques applying to various times scales and averaging periods. On the longest time scale is **trend analysis**, using averaging periods ranging from months to millennia. Recent examples include analyses of temperature and precipitation for the globe and the hemispheres (Hansen and Lebedeff, 1986, 1988; Jones et al., 1986a, 1986b; Bradley et al., 1987) and for areas within the U.S. (Hatch, 1983). Although the techniques are commonly straightforward, major efforts are needed to ensure that the data used are of sufficiently high quality to allow the establishment of valid trends (e.g. Finkelstein et al., 1983; Markee, 1985). Care must also be taken in amalgamating station records when area average values are required (Karl and Jones, 1989). While the major effort

recently has been to identify the climate change signal from the noise of normal climate fluctuations, the judicious extrapolation of trends provides a baseline from which scenarios can be built.

On a shorter time-scale the value of daily **time series analysis** has been demonstrated by LeBoutillier and Waylen (1988). The technique has been relatively little explored, but has potential applications in several fields, including agriculture and human health. In addition, the possibility of linking time series outputs to those of GCMs has been explored by Reed (1986).

An alternative method of obtaining daily values of weather elements is to use **weather generators**, which are commonly used in agricultural and engineering applications. These use stochastic modeling techniques (e.g., Brown et al., 1985; Alexandersson, 1985). One approach, common in agriculture, is to use a random number generator with the probability statistics of the elements of concern to give a synthetic stream of daily weather events (Larsen and Pense, 1982). These streams can be regarded as scenarios, because it is common to create several streams by starting with different random number seeds and to explore the implications of each before making planting or policy decisions. An alternative approach for producing synthetic daily values, common in engineering, is to create a "typical meteorological year" (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1972). This is a single year having random daily values which retaining the major features of the monthly means and higher moments of the observational record. Indeed, such standard typical meteorological years have been developed by the National Climatic Data Center (Hatch, 1983) for impact assessment purposes.

Almost all of the techniques within the Climatological Statistics module are very well developed. For scenario development purposes the major challenge is to use them in appropriate ways to provide the detailed information which complements information developed by other modules and thus contributes most effectively to the development of scenarios.

SYNOPTIC ANALYSIS

The objective of synoptic analysis is to identify the major "weather types" which affect a location, and to specify the frequency of their occurrence. Weather types represent the common synoptic meteorological situations of the area, examples being the passage of a front or depression or the presence of a stagnating high pressure system aloft. Because each weather type is associated with a particular range of values for all weather elements, the technique also allows assessment of the frequency distribution

of various combinations of climatic elements. The method provides regional climate summaries incorporating both day-to-day weather changes and monthly means and totals (Barry and Perry, 1973; Barry, et al., 1981), and "explains" regional climate differences (e.g., Hare, 1966; Henderson-Sellers and Robinson, 1986). However, it is also capable of producing detailed quantitative information. For example, Muller (1977) generated monthly probabilities of the occurrence of weather types favoring high air pollution concentrations around Shreveport, LA, and Unwin (1980) related the synoptic conditions to urban heat island magnitudes. On a longer time-scale Bryson (1966) used the method to explore the factors controlling the northern limit of the boreal forest in North America, while Borchert (1950) investigated the vegetation zones of the American Mid-west. Synoptic analyses can be linked with the atmospheric circulation studies (e.g., Vogel and Huff, 1978), so that it is potentially possible to link this module with outputs from process models.

The foundation of the method is analysis of daily weather data to determine the appropriate suite of weather types. The suite is made as small and manageable as possible, usually around 10, while retaining the main features of the day-to-day weather variations. The traditional approach is through visual inspection of daily weather maps, but this is time consuming, subjective and dependent on the skill of the analyst. Further, the results are only applicable to one small area. Unfortunately there is at present no means of automating the procedure. Consequently, attempts are being made to produce objective methods (Ladd and Driscoll, 1980; Key and Crane, 1986). Although complete objectivity is proving to be elusive (Yarnal and White, 1987; Yarnal et al., 1988), development efforts are underway using both statistical and spatial techniques.

Statistical Synoptics are being developed using multivariate statistical methods. They were used by Jones and Kelly (1982) to identify the frequency of various weather types in Britain, and by Kalkstein and Corrigan (1986) to determine the characteristics of various air mass types as an aid in air quality assessments. Building on these, a more flexible approach has been introduced by Todhunter (1989). He used a principal component analysis of daily observations at Boston, MA, to identify the major weather types, followed by a cluster analysis of the types to develop a synoptic climatology for the station. Hammer et al. (1987) used a similar approach, modified to incorporate a modelling component, to develop information for agricultural use in the Mid-west. Although the applicability of the method in other areas and climates has not been tested, and the spatial stability of the results is unknown, the whole method can be automated. Thus it represents a potentially fruitful line of research, offering the possibility of developing a

scenario module containing information pertinent to the frequency distribution of various climatic elements individually and in various combinations.

Spatial Synoptics represent a second, relatively untested, approach to objective synoptic analysis. The spatial domain is emphasized by using the techniques available with Geographic Information Systems (GIS). Such systems offer the possibility of examining the synoptic situation in new ways. For example, they may play a major role in the identification of the frequency and location of depression tracks, a key element of mid-latitude climates, and one where links with GCM outputs are beginning to be established (Lambert, 1988). There have been numerous studies of such tracks, for the Northern Hemisphere (Whittaker and Horn, 1984), the U.S. (Reitan, 1979), and the eastern seaboard (Hosler and Gamage, 1956; Colucci, 1976). All have counted depression passages through prespecified grid boxes. This is known to lead to errors (Kelsey, 1925; Hayden, 1981), but the more appropriate method, counting the passages within a specified search radius of a given point (Neumann and Pryslak, 1981; Taylor, 1986), was regarded as computationally too complex. However, this is the type of analysis where GIS excels, and the establishment of techniques for the analyses of secular variations in depression tracks and frequencies is likely to prove an important tool within the synoptic analysis module.

3.3 *LINKAGE TECHNIQUES*

The above discussion indicates that few of the modules, either process or empirical, can stand alone as scenario production techniques. There must be linkage between them. The most desirable linkage is one whereby the output of one module feeds directly into the subsequent one. For such links the modules must have appropriate types of outputs and inputs. In many cases this mainly involves a matching of temporal and spatial scales. Consideration of the potential for such links should be encouraged during module development. At present, however, few direct links can be established and other linkage techniques must be used.

There is relatively little experience in the creation of linkage modules and no methods are well established. Indeed, this is an area of research which has itself been stimulated by the need for scenario development. Nevertheless, several lines of approach can be suggested within the modular context. These must, in most cases, be speculative, and indicate general lines of approach rather than refer to already well-established techniques.

ADJUSTMENT METHODS

In cases where the outputs and inputs cannot legitimately be directly connected, it may be possible to provide the necessary connections through simple adjustments of the outputs of one module. This can be undertaken both statistically and spatially.

Statistical adjustment has been used in several scenarios (e.g., Smith and Tirpak, 1988; Cohen and Allsopp, 1988). In these, future conditions were established by taking the difference (for temperature) or the ratio (for precipitation) between GCM results in the present and the perturbed climate and superimposing it on the observational results for the present climate. This statistical adjustment approach is attractive because it gives great weight to the GCM results in their area of strength, broad scale temporal changes in response to changed atmospheric conditions, while de-emphasizing their weakness, specification of the present climate. Potentially, it allows specification of the future climate in considerable detail. The underlying assumption, however, is that every point within a GCM grid cell will respond equally to the change. This is physically unlikely, and Cohen and Allsopp (1988) note the difficulty of ascribing realistic values to the water surfaces of the Great Lakes, any "lake effect" being smoothed out in the spatially integrated results. Since this problem will occur whenever there are variations in surface type or configuration, methods must be developed to incorporate the spatial variability within grid-cells into the statistical adjustment linkage technique so that detailed scenarios can be produced.

Spatial Adjustment techniques have been proposed by Nielson (1987). He postulates that some of the current GCM outputs need to be spatially "shifted" from their current positions because of limitations in their ability to incorporate the influence of surface features such as the Rocky Mountains. He finds, for example, that a comparison of observational and GCM outputs for the current climate gives better results if the latter are geographically shifted somewhat. Thus similar shifting when the models are used to indicate future climates is likely to give more realistic results. The potential of this technique must be explored.

TRANSFER FUNCTION METHODS

It is possible that "transfer functions" can bridge the gap produced by the scale mismatch between the GCM outputs and the local detail required by scenario users. This is a relatively new concept, and there have been few investigations. Nevertheless, it is clear that two lines of approach, statistically based and process based, are available.

Statistical Transfers were pioneered by Kim et al. (1984), who identified the need to develop transfer functions to transform GCM outputs to local conditions, their so-called "Climate Inversion Problem". They used the observational record for a series of Oregon stations to develop statistical relationships between the area-averaged local climate and GCM grid-cell outputs for current and changed climate conditions. Although the results were somewhat ambiguous, reflecting this first attempt at a solution, the concept of developing statistical transfer functions from GCM outputs to surface climate should be explored further, using a range of statistical techniques.

Process Transfers are also designed to address the climate inversion problem, but emphasizing process transfer functions rather than statistical ones. Because the GCM "surface" climate is a spatially smoothed one applicable to conditions some distance above the surface and away from the major influence of the planetary boundary layer, there is a need to link the detailed surface climate with the smoothed near-surface one through that boundary layer. Thus Chen and Robinson (1989) postulated that scenarios could be created by linking, both statistically and through modeling efforts, the current upper-air climate and the surface one, in essence producing a transfer function between them. A similar problem is being addressed, in the meteorological context, by Klein and Bloom (1987). Again, this approach has not been fully tested but merits further exploration. In particular, more explicit treatment of the role of the boundary layer in the transfer function is needed, which may require the inclusion of local process models.

SYNTHETIC METHODS

A "no-skill" approach to scenario development is to play simple "what if?" games: "If the climate changes by this amount, what is the impact?" If the results are to have any use, the postulated changes must be realistic, and thus come from consideration of both model results and empirical observations. In this module, therefore, the emphasis is on the potential impacts. It has been used to some extent in the climate context (Gleick, 1987), and has been widely used in economics and political theory (Lave and Epple, 1985). It provides primarily a means of assessing the sensitivity of particular effects to changes in climate. As such, it does not contribute directly to scenario development. Again, however, it has potentially an important role, because it serves to focus attention on the sensitive areas, and thus may provide guidance on the areas of concentration for scenario development.

3.4 *USING MODULES FOR SCENARIO DEVELOPMENT*

The individual modules identified above provide information necessary for scenario development, but cannot be used alone to produce scenarios without using many assumptions and introducing great uncertainty. By linking various modules together to produce a scenario, however, the number of assumptions can be reduced and a more scientifically sound scenario produced. Indeed, the modules were developed to provide such linkage (Figure 2). In particular most scenarios must start, implicitly or explicitly, with the future climate conditions as sketched by global model outputs. Other modules must then be used to transform this broad-scale information into the detailed information needed for impact assessment.

An almost infinite variety of module combinations is theoretically possible. However, linkages are constrained by the input and output requirements of the various modules, especially the temporal and spatial scales indicated in Tables 3 and 4. In addition, some obvious potential linkages have already been noted in the preceding narrative. Consequently some promising lines of approach are beginning to emerge (Figure 3). These are presented here in general terms, without consideration of the time and space scales involved or the types of output products. The first approach (Figure 3 A) depends entirely on the use of process models to transform the generalized GCM outputs to local conditions, with direct linkages between the models of various scales. The next two approaches use a combination of process model and empirical method modules, first (Figure 3B) in a simple, straightforward manner linking them using adjustment methods, the second (Figure 3C) involving a more complex approach and transfer function linkage. These two are presented separately because the former is likely to be more appropriate for relatively rapid, but somewhat unscientific, scenario development, whereas the latter is likely to involve more research steps, take somewhat longer to develop, but produce sounder results. The final approach (Figure 3D) is also relatively straightforward, but has an emphasis on the assessment of the sensitivity of impacts to climatic changes rather than on scenario development itself. It provides a means for rapid identification of those climatic elements of most importance to users, vital information when user-oriented scenarios are to be produced.

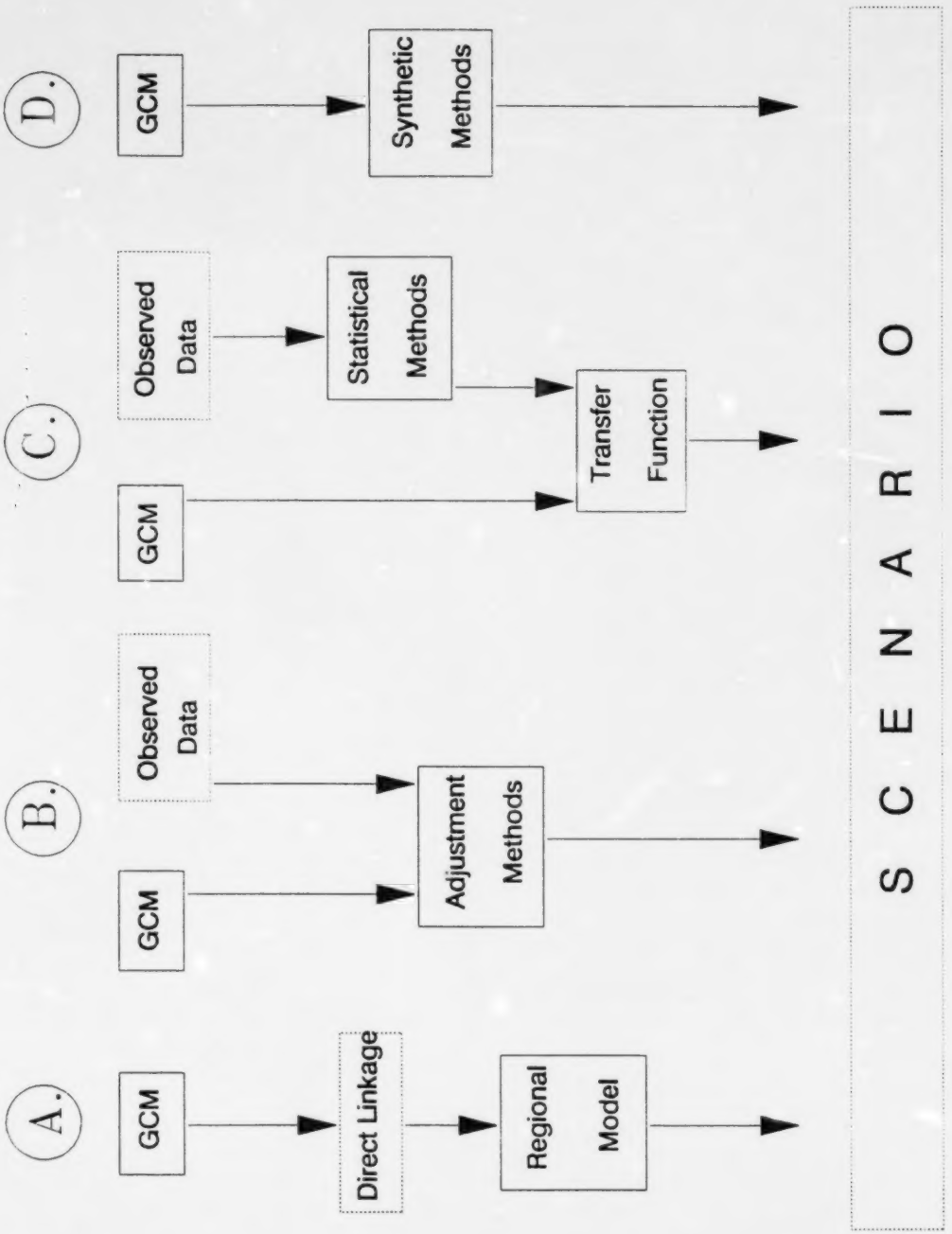

FIGURE 3. Schematic diagrams of the general approaches to scenario development using linked modules.

3.5 *DEVELOPMENT OPPORTUNITIES*

The preceding sections suggests that there are a great many options available for scenario development. However, modules have been presented without consideration of their present state of development, the current level of research effort in refining the methods (whether for scenario development or not), or their potential to be converted into scenario development techniques. Although brief indications of some of these considerations were given in the descriptions earlier, it is necessary for the production of a scenario development strategy to assess these more comprehensively.

For each module the state of current development, the current level of research activity, and the estimated effort needed to make them scenario development techniques is given in Table 5. Also included are brief statements, drawn from the longer discourse above, concerning the potential applicability of the modules to scenario development.

In Table 5 the current level of development of the modules (column 2) is classified into low, medium, and high. This is an assessment of the technique itself in terms of its theoretical foundation, the tests which have been made of its strengths and weakness, and the availability of well-established methods for its use. No consideration is given in this column of its suitability for scenario development per se. In Column 3 the current level of research is couched in a similar tripartite form. Here the assessment is based primarily on the numbers of recent papers addressing the technique or on current research projects. The fourth column provides a qualitative assessment of the effort needed to take the technique as it currently exists and to transform it into a true scenario development technique. This, again, is a three part qualitative assessment. In general, those needing low effort are modules where the technique has already been used or is directly applicable and only needs a test to determine suitability. The medium effort category includes those techniques where the steps needed for the transformation are reasonably clear, but where some underlying work is needed before they can be tested. Techniques are assigned to the high category when either the translation method is currently very unclear or where the method itself is not well developed. The fifth column suggests the potential value of each module as a scenario development technique. Here the assessment is based on the ability of the technique to provide, or be linked to other modules to provide, the detailed, local-scale outputs needed for impact assessment. Techniques which have the potential to provide scenarios of wide application have tended to be ranked higher than those

TABLE 5: STATUS OF SCENARIO DEVELOPMENT TECHNIQUES

MODULE	CURRENT DEVELOPMENT	CURRENT ACTIVITY	REQUIRED EFFORT	APPROACH VALUE	COMMENTS
PROCESS MODELS					
Global					
General circulation models	Medium	High	Medium	High	Vital in all efforts
Global chemical models	Medium	Medium	High	High	Must be incorporated eventually
Regional					
Numerical weather models	High	High	High	Medium	Long-term possibility
Regional climate models	Low	Low	High	High	Very important approach
Regional chemistry models	Medium	Medium	Medium	High	Important for understanding & applications
Mesoscale					
Mesoscale meteorological	Medium	High	High	Medium	Very long-term possibility
Urban chemistry models	High	Medium	Medium	High	Primarily an application
Surface boundary models	Medium	High	High	High	Important for many applications
EMPIRICAL METHODS					
Circulation Analysis					
Circulation indices	Medium	Medium	High	High	Very important for some approaches
Teleconnections	Medium	High	High	Medium	Important for regional comparisons
Analogue Techniques					
Instrumental analogues	Medium	Low	Low	Medium	Useful for impact sensitivity studies
Proxy analogues	Medium	Medium	Medium	Medium	Provides direct connection to impacts
Spatial shifts	Low	Low	Low	Medium	Can provide evocative summary
Climatological Statistics					
Mean statistics	High	High	Low	High	Very important, vital for some impacts
Event statistics	Medium	Medium	Medium	High	Very important for some impacts
Temporal statistics	High	Medium	Low	High	Very important for trends
Synoptic Analyses					
Statistical synoptics	Medium	Medium	Medium	High	Very important for some approaches
Spatial synoptics	Low	High	High	High	Potentially very useful
LINKAGE TECHNIQUES					
Adjustment Methods					
Statistical adjustment	Medium	Medium	Low	Low	Limited scientific foundation
Spatial adjustment	Low	Low	Medium	Medium	Potentially important
Transfer Function Methods					
Statistical transfers	Low	Low	High	High	Very important
Process transfers	Low	Low	High	High	Very important
Synthetic Methods	High	Low	Low	Medium	Important for sensitivity studies

whose application is restricted to a narrower field. The final column gives very brief comments about the role of the technique in scenario development. This is to a large extent a phrase summarizing the detailed consideration undertaken previously.

Table 5, however, considers the modules only in isolation. Although one set of modules is linkage techniques, there are also development opportunities associated with the linking of modules. Figure 3 indicated some potential approaches. Each of these provides development opportunities. For all except the complex combination approach (Figure 3C) these opportunities are mainly in the direct development of specific scenarios to meet user needs. Progress can be achieved by assessing the user needs in a particular context, choosing an appropriate module, and exploring the possibilities of refining and expanding it to meet the needs. For the complex combination approach, however, the opportunities are somewhat different. Here the emphasis is on the use of various modules to provide a scenario which is as scientifically sound as possible. Hence various combinations of techniques must be considered, developed, and tested. Some possible combinations, which are either beginning to be explored or have been suggested, are sketched in Figure 4. It is immediately apparent that these are more complex than the methods already in use (Figure 3), and it is likely that major research efforts are needed if these postulated methods of creating scientifically sound scenarios are to be explored.

Taken together, Table 5 and Figures 3 and 4 provide a survey of the research needs and opportunities for scenario development in a general context. Specific research directions must take into account the user needs. Thus the following section addresses these needs, the more focussed research strategies being developed in Section 5.

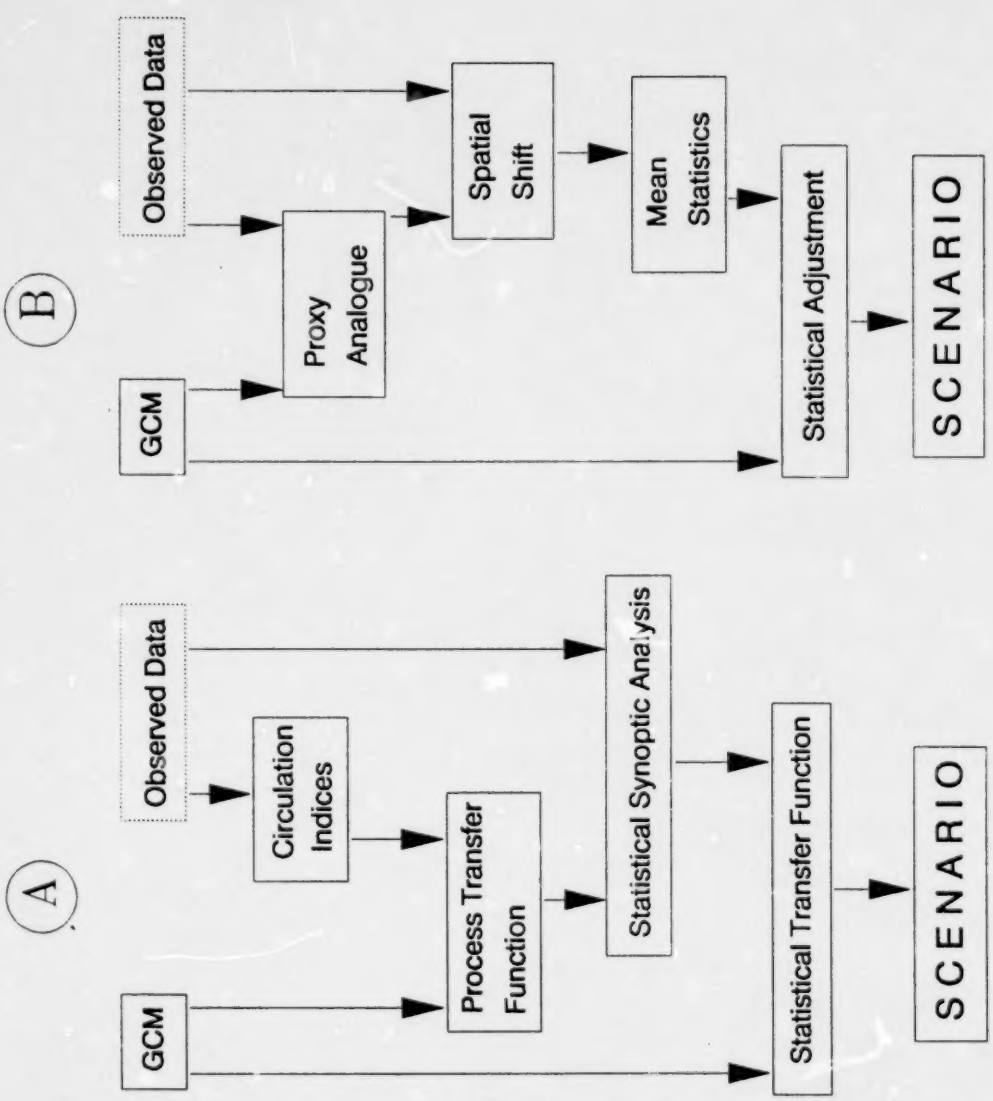

FIGURE 4. Schematic diagrams of approaches to scenario development using several linked modules.

SECTION 4

USER NEEDS ASSESSMENT

The second major piece of information required for scenario development is specification of the climatic information needs of those undertaking impact assessments. The impacts involve a variety of disciplines, including water resources, ecology, air quality, and agricultural production. Therefore a wide variety of needs could be anticipated. However, for this analysis the requirement is for the identification of the major types of needs, expressed in a form which allows them to be linked with the possible scenario development approaches identified in the preceding section. Although some indications of such needs can be obtained from the published literature it was deemed most advisable to assess them in direct cooperation with people having experience with impact assessment.

4.1 *USER CONTACTS*

One major group with interest and experience in scenarios for impact assessment is the participants in the development of the EPA report to Congress on the impacts of climatic change (Smith and Tirpak, 1988). Members of this group, together with some other individuals who expressed interest in scenario use, were contacted, and their help in developing the specification of user needs was solicited. Thus the people selected to participate had previous experience in using climate scenarios for impact assessment in their fields of interest. In particular, they were considered to have the most experience in understanding the impacts of climate change. As experts in their fields, they would be most likely to know the specific data needs that would be most important for determining these impacts. Nevertheless, it was emphasized that these individuals should put aside both what they thought constituted "a scenario" and their knowledge of the limitations on the current scenario production methods, and consider what they thought would be the most useful pieces of information needed for impact assessment. They were asked to pay scant regard to the present practicality of their request, but rather to think in terms of an information target to which scenarios should aim.

The process started with some initial informal telephone contacts. The majority of those contacted in this way noted that vital questions were being asked which required a great deal of thought, and so requested that some form of "questionnaire" be constructed to help them frame their responses.

TABLE 6: QUESTIONS ASKED OF IMPACT ASSESSORS

1. lists and rankings of important climatic elements
2. the desired time intervals for each of these factors
3. the summarizing statistics for each of these factors
4. the types of individual climatic events of importance
5. the spatial resolution for each factor
6. the geographic areas of interest
7. the parts of the annual cycle that were of interest
8. the need for steady state or transient scenarios
9. an evaluation of the format of the scenarios used in the report to Congress and recommendations for changes
10. the names of the effects models used

Consequently, a very informal and open-ended letter was sent to all potential participants in this user needs assessment, indicating the types of information needed. For the present analysis this can be formalized, and a list of 10 questions specified (Table 6). Hence the rest of this analysis treats this very informal process as a "survey".

Fifty-six questionnaires were sent out in December 1988 to individuals at universities, private research centers, and in some Federal agencies. Overall, these groups have interests in hydrology, air quality, climate, water quality, agriculture, insects, sea level change, and ecology; and all have research interests in the impacts of climate change. This provides a broad range of interests, and for convenience in the detailed analysis of responses, interests were divided such that hydrology, water quality, and sea level are grouped as "Aquatic"; climate and air quality are grouped as "Atmospheric"; agriculture, insects, and ecology are grouped as "Terrestrial". The breakdown in the number of questionnaires sent to these individuals is shown in Table 7.

Respondents were asked to be as quantitative as possible. For example, question 1 asks that climatic factors of importance be listed and ranked in the order of their importance for each individual's research needs. In this manner, it was hoped that from all of the responses a pattern of data needs might become apparent in some hierarchial form. By looking at those

TABLE 7: MAJOR AREA OF EXPERTISE OF QUESTIONNAIRE RECIPIENTS

	Number Sent	Number Received
Aquatic	25	8
Atmospheric	7	3
Terrestrial	24	9

factors most often requested by the greatest number of respondents, both the specific data needs and the range of data types kinds could be determined. Some of these needs might be inconsequential to many researchers, but vital to others.

Respondents were also asked to add as many comments as they wanted. They were told in the cover letter that the results of this questionnaire would guide the development of preliminary scenarios which would be supplied to the research community, and that there would be subsequent assessments of these scenarios by that community. Thus it would be beneficial to the community if they would take part in this user needs questionnaire because it would affect the type of data which would be available from scenarios in the future.

There were 20 responses to the 56 questionnaires that were sent out. However, of these 20, only 14 responses were from those who were actually sent questionnaires. Some questionnaires were sent to two or more colleagues at the same institution and only one responded. At five other institutions the questionnaire was circulated to other colleagues who also responded. Some single responses were syntheses of discussions among colleagues at an institution. All this additional input was welcomed by us and is much appreciated. The responses came primarily from university and Federal research groups.

The responses ranged from extremely detailed to terse. Part of this may be due to differences in interpretation of the meaning of climate scenarios. In fact, beyond general definitions similar to that given at the

beginning of this report, there is no clear consensus on what constitutes a scenario. Certainly a climate scenario means different things to different research groups. The responses suggest that this variation in definition might be related to field of interest. A few of the responses showed that even some of these experts do not necessarily understand the implications of scenario production in their fields. Close cooperation between scenario producers and users is clearly needed.

The selection of respondents for this questionnaire was biased and may not be representative of the whole community since the questionnaire was sent primarily to those who worked on the report to Congress. Nonetheless, because the community of researchers who have looked at future climate change impacts is very small, the group we selected probably includes a fairly large percentage of them, so the results should be taken as reasonably reflective of the needs of the community at the present time.

4.2 *SYNTHESIS OF RESULTS*

Because of the free-form nature of the questions a large amount of interpretation and simplification of the responses was necessary For example, responses that included temperature, air temperature, and surface temperature were aggregated; and water vapor was taken to included absolute humidity, relative humidity, and dew point. Responses which considered time and space scales used a variety of nomenclature, so that some interpretation and simplicifation was needed. It was also clear that some responses used a priority rating of 1 (highest) to 5 (lowest), rather than 5 to 1 as requested. These were switched when it was clear that it was appropriate.

In the following sections the responses to the individual questions are discussed and either tabulated or interpreted. This summary will only present an analysis of the results, and cannot review many of the interesting and important - but unusual - requests for scenarios that were made.

Question 1: This question asked for a priority list of climatic elements that the respondents would like to have in future scenarios. Table 8 gives a list of those variables, with the percentage of the total number of responses that asked for that variable. Most respondents listed a number of factors, some included only a few. Other variables, not listed in Table 8, that were mentioned more than once included mixing depth, evaporation, growing season, storms, and glaciation.

TABLE 8: CLIMATE ELEMENT NEEDS OF IMPACT ASSESSORS

Variable	Percent of Respondents
Temperature	90
Precipitation	81
Wind	52
Radiation	48
Water Vapor	48
Clouds	29
Snow	20
Pressure	10

The question also asked that the elements be ranked into five categories, which we arbitrarily call very high, high, medium, low, and very low. This does not imply that the lower priority variables are unimportant. In some responses, more than one variable was listed as having the same priority, which was taken to indicate that they were of equal weight. The priority percent for each variable is listed in Table 9. The percentage given is based on the number of times that variable was listed and not the total number of responses.

Question 2: This question asked about the needed data interval, or the averaging period for the variables. The responses indicated that most researchers wanted the data interval of the scenarios to be a day or less, although they indicated that a data interval of a week to a month would be acceptable, but not desirable. Only 23% desired a data interval of no more than once a month (i.e., monthly averages).

Question 3: For each of the variables almost all responses asked for at least the mean or an associated statistic such as rainfall total amount. Some measure of variability, such as standard deviation or range also was usually requested. Another question asked specifically for special statistics or climatic events that would be of interest. There were many different requests, including precipitation descriptors such as rate, duration and intensity; and for summaries such as interannual variability.

TABLE 9: PRIORITY OF NEEDS FOR SPECIFIC CLIMATE ELEMENTS

Variable	Priority (%)				
	VH	H	M	L	VL
Temperature	84	11			
Precipitation	82	18			
Wind	18	27	18	18	18
Radiation	10	30	50	10	
Water Vapor	20	50	10	10	10
Clouds	33		33	17	17
Snow	25		25	25	25
Pressure	50			50	

Question 4: When the types of climatic events of importance were requested, responses centered around some measure of three kinds of events: droughts - 44%, thresholds - 33%, and storms - 39%. Some respondents asked for more than one of these: hence the total is greater that 100%. The term "thresholds" includes the number of occurrences of some variable greater than, or less than some predefined value, (e.g., number of days below freezing), or a combination of threshold and duration, (e.g., heat waves or number of days between last frost in spring and first frost in fall). The term "storm" includes the number of storms, severity, frequency, and storm tracks. There was also an interest expressed in data for extreme events that occurred relatively rarely.

Question 5: The questionnaire requested information on the desired spatial scale for the scenarios. The information is difficult to quantify because the responses used very different measures of distance and area. Some used a grid spacing or grid square area; some used a relative measure such as county, state, or crop reporting district. Most requests, however, were for spatial density that is considerably smaller than the present GCM grid, with many of the responses ranging from 100-km grid to counties. It was interesting that very few asked for integrated measures, such as the total rainfall over an area, or time-integrated amount of radiation. Perhaps that is because such information is not readily available from the normal data sources, and effects scientists aren't aware that it could be made available.

Question 6: The location of interest varied widely, corresponding to the normal area of research of the respondents. These included the Great Lakes, Southeast, far West, and other major geographic regions in the U.S. Only a few asked for scenarios outside the country. These requests may be the result of specific research interests of those who responded to the questionnaire and not necessarily representative of the entire scope of research in climate scenarios.

Question 7: To determine whether or not emphasis should be placed on scenarios for any one particular season, a priority ranking of each month was requested. The responses were evenly divided into three groups: (1) those that ranked summer months high, (2) those that ranked all months evenly, and (3) others. The "others" was a mixed bag of winter, winter and spring, and strange patterns of months we haven't been able to decipher.

Question 8: To the question of whether the scenarios should be for a steady-state climate, or for a transient response climate, most responded that they would like to see both; with the transient response being the second choice. However, the ambiguity in many of the responses suggests that this is a question needing fuller discussion.

Question 9: When asked whether the format of the earlier EPA scenarios were satisfactory, half responded yes, and half no. Those who were unhappy with the first effort suggested the need for better documentation, better time and space resolution, better access to information, and the need for additional information. The half that liked the first effort had some quite complementary things to say about the effort and the support they received.

Question 10: The respondents were asked which models they were using in their own research. This question was designed to give some insight into the particular needs of the effects modeling community. Most respondents who are using models are using some kind of agricultural or crop model, such as the CERES series (CERES Wheat, Maize, Rice, etc.). Other models included hydrological, lake evaporation, ice melt, pesticide movement, water quality, and air quality models.

To determine if the field of interest of the user dictated responses to any questions, the responses were reanalyzed after they were sorted into the three basic user categories indicated in Table 7. Other, and finer, divisions are possible, but more categories may not be advisable when considering the limited number of responses. In any case the results indicate that these groups did not differ significantly from each other, or from the group as a whole. The choice of variables and the priority remained relatively constant,

as did the time and space scales. About the only difference of note was the interest of the hydrological group in winter precipitation and snow, which, of course, has a major impact on water supply.

4.3 *MAJOR USER NEEDS*

This information is summarized to identify the major user needs for climatic information (Table 10).

A time scale of one day will, with the exception of the unusual events, satisfy most of the user needs. The daily values must, however, be capable of producing a time average allowing for simpler scenarios for those who require them. Shorter time scales and unusual statistics may be needed by only a small minority of users.

TABLE 10: SUMMARY OF MAJOR USER NEEDS IDENTIFIED FROM DISCUSSIONS WITH SCENARIO USERS

Time Scale

Daily values - not necessarily a sequence of daily weather

Space Scale

100-km x 100-km grid - specific needs highly variable

Information Needed

1. Simple descriptive statistics for individual elements
   (means and variance, totals, extremes, etc.)

2. Climatic anomaly information, especially concerning **drought**
   (magnitude and persistence of events)

3. Threshold values
   (probability of values significant for particular impact)

4. Synoptic information, especially for **storms**
   (sequences of events and combinations of elements)

Spatial scale requests were much more variable, but it seems that a goal of a 100-km grid would satisfy most users. However, variables such as convective rainfall and orographic effects will certainly not be represented in this grid, and are needed in many important cases, so some accommodation will be necessary for these cases.

The response to questions about the actual climatic elements needed allows the division of the information needs into four broad categories (Table 10). In large measure these reflect current experience with scenario use, in that the first can be specified in some detail, the others in many cases only being hinted at or approached obliquely.

Information needs for specific elements (Table 10, "Information needed", Item 1), couched in terms of simple statistics needed, were requested with a good deal of specificity. Thus the most important variables for effects research, and hence scenario development, are temperature, precipitation, wind, radiation, water vapor, cloud cover, and snow. Particular data needs for each variable are as follows:

Temperature - daily average, maximum and minimum or variability

Precipitation - daily total, time and space distribution statistics, rain or snow. Some guidance on spatial integration or interpolation will be necessary.

Wind - daily arithmetic average and variability, at 10 m and through the mixing layer. Average transport speed and direction.

Radiation - daily average incoming solar, and variability.

Water Vapor - daily average and variability. This can be expressed in one or more ways, as absolute or relative humidity, vapor pressure, dew point, etc.

Clouds - Daily average cloud cover and type.

Snow - Snow depth, or water equivalent. Daily snowfall is not important for this variable, but spatial extent and elevation differences are.

The second information need category, usually mentioned in connection with drought, was for information about the persistence of events for relatively long time periods (weeks or months) over broad areas (a state or group of states). This can be interpreted as the need for anomaly information for both individual elements and for several elements in combination. This must be a major concern in scenario development strategies.

The third category is for information about thresholds. Although there is some concern for "record breaking" events, the majority of people expressed more interest in the probability of occurrence of "significant" events such as number of days below freezing or the probability of cloudless conditions for several consecutive days. Although some of these may be estimated from the simple statistics considered earlier, they are generally regarded as being very important to effects research. Hence some scenario development strategies must be aimed specifically at ascertaining these thresholds.

The final category is labelled "Storms". This word was mentioned by numerous respondents, and appears to cover a variety of connotations, from the ecological damage of an ice storm, through hydrologic concerns with flash flooding, tornado and hurricane frequencies, to the frequency of passage of mid-latitude depressions. Thus this category is interpreted as expressing the need for information about particular weather events on the "synoptic" (weather forecasting) scale, including concern with the time sequence of events and a combination of climatic elements. On the finest spatial scale, this is likely to provide a major challenge for scenario development, although possibilities exist on a broader scale.

It was clear from the analysis of the individual responses to this questionnaire that we weren't prepared to ask all of the right questions, and that the effects research community didn't have enough experience working with climate scenarios to answer the questions we did ask as fully and completely as needed. Further interactions between producers and users is needed. Indeed, it is a vital process, so that their scenario needs can be more clearly defined. As the community grows we will also get a wider sampling of user needs, which will help to define future scenario production plans.

SECTION 5

RESEARCH NEEDS

The objective in this section is to link the various research opportunities identified in Section 3 to the major user needs identified in Section 4, to develop a strategy for EPA-sponsored research into scenario development.

5.1 *PROGRAMMATIC NEEDS*

In developing such a strategy, there are two major considerations:

1. The need to develop some scenarios in the near-term.

   As part of the overall scheme of the EPA Global Climate Change Research Plan, and as the explicit strategy adopted here, an iterative approach to scenario development must be used. As such, it is necessary to produce some scenarios in the near-term which can be provided to those assessing impacts. Although these must contain the best and most pertinent information possible, an equal focus is on assessing the user's "reaction" to the nature and quality of the scenario which is provided. This information can then be used in the next iteration to produce a new set of scenarios which are both more scientifically sound and more appropriate for the user.

2. The need to support research designed to develop, in the long-term, more scientifically sound scenarios.

   New methods of scenario development must be explored in an explicitly research mode. A variety of efforts, involving several modules, and with varying levels of immediate relevance to scenario development, must be fostered. Both user needs and scientific credibility must be considered. It is anticipated that the results of this type of research, as they become available, will be incorporated into the subsequent generations of scenarios.

Although EPA has a specific, mandated role in the production of assessments of impacts of potential climatic changes, and specific research strengths because of its traditional mission, it is not operating in isolation. A considerable body of research, from a variety of perspectives, is being undertaken or sponsored by several international bodies, government agencies and private groups (Environmental Protection Agency, 1989). EPA

must be cognizant of, and coordinate with, this work, both to avoid unnecessary duplication and to seize opportunities to use legitimate research results in the further development of scientifically sound scenarios.

5.2 *RESEARCH STRATEGY*

The research strategy must be designed to approach the ultimate aim of producing scientifically sound scenarios tailored to the specific needs of an impact assessor, and capable of being used in a routine, operational, setting.

No method of scenario production is currently so well developed that it can be taken directly and transformed into a routine scenario production procedure. There are varying degrees of research needs and opportunities in all of the modules (Table 5), and there are needs to investigate ways of linking the modules (Figures 3 and 4). These is a similar wide range in the current specificity of user needs (Table 10).

Thus the strategy recommended is to use an iterative approach to scenario development (Figure 1). Relatively simple scenarios are produced, used for impact assessment, and evaluated from scientific credibility and practical value. Appropriate refinements and modifications are made and a new scenario produced, which starts the next iteration. Throughout, guidance is provided by the information in Tables 5 and 10 and Figure 3 and 4.

It is recommended that the research projects be divided into three groups: short-term, medium-term, and long-term. This represents three iterations, and three "generations" of scenarios. Within each iteration are three thrusts: development of actual scenarios for that particular generation; research within modules and module linkages to provide information needed to allow refinement in the next generation; and ancillary activities which are necessary to meet the overall EPA goal of providing scenario development methods which can be used by anyone wishing to undertake impact assessments. The scenarios at each stage are aimed primarily at the four categories of user needs identified in Table 10.

It is assumed throughout that research undertaken by bodies other than EPA will be incorporated whenever appropriate. Thus it is anticipated that research into atmospheric physical processes and the development of global-scale climate models will continue under the auspices of other agencies. The major EPA roles will be to encourage such work with support in specific areas and to develop appropriate output products and methods of

scale linkage. EPA will also continue to play a major role in the development of atmospheric chemical models and in their linkage with the physical models. Further, while the major users of scenarios will be the various groups within EPA having responsibility for assessment of ecological, water resources, and air quality impacts, it is also anticipated that scenarios will be developed in consultation with other groups, for a wide range of impacts. Indeed, these other groups are likely to play significant roles in the development and refinement of modules appropriate for their needs.

5.3 *RECOMMENDATIONS*

For each of the three generations separately, recommendations are given for scenario development activities, module research efforts, and other investigations necessary for the EPA program. Specific recommendations for techniques to be developed and tested are couched in terms of the modules and their major subdivisions, as given in Tables 2 and 5.

SHORT-TERM

The short-term period emphasizes the development of usable output products within 1 to 2 years of initiation. Recommendations are given in Table 11.

The scenarios to be developed are first generation ones. Although they are aimed at the user needs identified in Table 10, these needs will be addressed only in a rather general way. These scenarios build in part on existing "zero generation" scenarios and, like them, emphasize approaches which combine GCM outputs with empirical methods. Although these should provide useful impact-oriented output, an equal focus is on the assessment of the user reaction.

Four scenario development efforts are recommended. The first two addresses the user need for simple descriptive statistics of the new climate. GCM results can be used to provide the boundary conditions and various Mean Statistics techniques should be explored to provide information about means and variances. For example a principal component analysis of spatial and temporal variability in past conditions when regional temperatures approximated the GCM values, could provide the scenario. The first, and potentially simplest, scenario is a Temperature Variation Scenario. Here GCM results and empirical analysis techniques are well-established. The second effort is a Precipitation Variation Scenario. This is potentially more difficult since GCM results are ambiguous and the empirical analysis techniques for an event-based element such as precipitation, are not as well developed.

TABLE 11: RECOMMENDATIONS FOR SHORT-TERM RESEARCH EFFORTS

Scenario Development:

- o Develop Temperature Variation Scenario:
  General Circulation Models + Mean Statistics
- o Develop Precipitation Variation Scenario:
  General Circulation Models + Mean Statistics
- o Develop Temperature Threshold Scenario:
  General Circulation Models + Event Statistics + Temporal Statistics
- o Develop Synoptic Event Scenario:
  General Circulation Models + Circulation Indices + Statistical Synoptics + Direct Linkage

Module Research:

- o Explore statistical transfers:
  Linking General Circulation Models + Mean Statistics
- o Explore spatial adjustment:
  Linking General Circulation Models + Proxy Analogues
- o Explore Process Transfers:
  Linking General Circulation Models + Surface Boundary Models
- o Refine Climatological Statistics Module for short-term temporal variability:
  Mean Statistics + Event Statistics + Temporal Statistics

Ancillary Activities:

- o Undertake sensitivity studies:
  General Circulation Models + Synthetic Methods
- o Review the state of the art for the linking of physical process models

Although the results from both scenarios will begin to satisfy a user need, these effort are also directed toward gaining experience prior to considering other more complex elements and combinations. They form the foundation for consideration of climatic anomalies, leading to the eventual development of specifically drought-related scenarios.

The third scenario development effort will also use GCM and observational temperature information, in this case using Event Statistics, to provide single-element threshold information. Again simple techniques assessing the probability of exceedence of particular thresholds using the instrumental records, with GCM values providing the boundary conditions, are

appropriate. Although thresholds are needed in a variety of fields, consultation with users during and after this effort is particularly important to elucidate the various possible meanings of "threshold", so that outputs will be useful. This scenario method also looks forward to more refined scenarios involving other climatic elements singly and in various combinations.

Methods of statistical synoptic and circulation analysis will be used in the fourth scenario to provide information about future synoptic event probability. Objective synoptic analysis can be used to determine the frequency of various weather types as a function of circulation index. The results can be combined with circulation estimates from GCMs to produce the scenario. Although at this stage the scenario does not specifically address the user need for storm information, but the total series of synoptic events in an area, it has immediate relevance in specifying the frequency of events, and provides the expertise leading to specific consideration of storms.

In addition to these scenarios, four areas of basic research within modules are proposed. The first three focus on the scale problem of estimating local-scale conditions from the broad-scale GCM outputs, and thus are directed toward explorating the various links between modules. **As with the scenarios, all treat GCM outputs as the driving force**. The first research area explores statistical transfers for refining the GCM information to provide realistic local information about means and variations of surface elements. Although the prime focus initially must be on temperature and precipitation, the elements most in demand, links between other elements, including humidity, wind, and radiation must be established. The second module research area has a similar rationale but an entirely different approach. Here the possibility of using spatial adjustment is explored, emphasizing a spatial comparison of modeled and observed conditions prior to suggesting temporal variability. Thus these two module areas provide complementary approaches. The third module to be explored seeks to specify process-based transfer functions to link GCM outputs to the surface climate. Here the use of surface boundary models to transform the average near-surface GCM outputs to the actual surface climate, is explored. In particular, the potential role of modified or newly formulated surface energy budget and water balance models must be investigated. This activity is explicitly process oriented, and represents the first phase of a transition from the almost exclusive reliance on empirical methods toward scenarios which are more soundly process based. The fourth research area is related to user concerns with short-term climate variability, exploring statistical methods for their specification in non-stationary situations. The research, which must be partly theoretical, should investigate the strengths and weakness of the

various methods of assesing variability not only for single elements but also for various elements in combination, so that user needs for wind-chill factors or evaporation rates can be met.

In the "Ancillary" category are two recommendations. One is to undertake sensitivity studies using, with GCM outputs as a guide, synthetic methods. This work is designed to be undertaken in consultation with scenario users, identifying not only the major elements likely to change but also those whose change will have a significant impact. It is anticipated that this work will also increase user awareness of the types of information which can be expected from scenarios, and thus be of great assistance in refining user needs. The second activity in this category is a review of the state of the art in physical modeling, directed toward identifying promising lines of research where scale linkages are likely to be possible in the not too distant future.

MEDIUM-TERM

The medium-term projects contain second generation scenarios and deal with activities capable of producing useable outputs within three to four years. The projects are shown in Table 12.

The scenarios to be developed, being second generation ones, should benefit from experience in developing the first generation, from user response to them, and from the earlier modular research. Hence the targets can be more specific, process models other than GCMs can begin to be incorporated directly, and more climatic elements can be involved. As a result of all of these, it is anticipated that these scenarios will be both more scientifically sound and also more useful.

There are four scenario development activities. The first three evolve directly from the first generation efforts. The first, a Drought Anomaly Scenario, evolves from the earlier efforts to specify basic statistics for temperature and precipitation. Here the simultaneous variation of these two elements is involved. Their influence on soil moisture, a vital concern for agricultural drought, is estimated through the use of surface process models and process-based transfer functions, which have themselves been developed through earlier module research. Since GCMs have already been used to specify drought directly, albeit in a primitive way, there is also an opportunity to compare results from two basically dissimilar methods and to estimate the value of the more refined information which can be anticipated from the method explored here.

TABLE 12: RECOMMENDATIONS FOR MEDIUM-TERM RESEARCH EFFORTS

Scenario Development:

- o Develop Drought Anomaly Scenario:
  Use: previous Temperature Variation Scenario
  : previous Precipitation Variation Scenario
  Incorporate: Surface Boundary Models + Process Transfers

- o Develop Event Threshold Scenario:
  Use: previous Temperature Threshold Scenario
  previous Synoptic Event Scenario
  Incorporate: Event Statistics + Regional Climate Models

- o Develop Element Variation Scenarios:
  Use: previous Temperature Variation Scenario
  : previous Precipitation Variation Scenario
  Incorporate: Mean Statistics + Statistical Synoptics

- o Develop Spatial Shift Scenario:
  General Circulation Models + Spatial Shifts

Module Research:

- o Explore direct linkages for meteorology/climatology process models:
  General Circulation Models + Regional Climate Models + Numerical Weather Models

- o Explore methods of spatial distribution analysis:
  Current and Paleoclimatic Shifts + Spatial Synoptics + Spatial Adjustment

Ancillary Activities:

- o Explore scenario documentation needs:
  (in cooperation with producers and users)

- o Review the state of the art for physical and chemical model links

The second scenario, the Event Threshold Scenario, is designed to provide information about events having thresholds which are expressed as a combination of several elements and where persistence for several days may be important. These include, for example, mixing height and wind speed for air quality problems or wind, humidity, and radiation for evaporation concerns. This effort builds on experience with the first generation Temperature Threshold and Synoptic Event scenarios, and incorporates the results from the earlier statistical methods research. The resulting combination, although still with a strong empirical base, includes the direct linkage of processes through the synoptic scenario. The output, possibly

couched in terms of the probability of a run of days with high evaporation rates, also has the potential to be linked and compared with regional climate model outputs. This represents a first stage in the incorporation of such models.

Methods of developing descriptive statistics for elements other than temperature and precipitation, Event Variation Scenarios, are explored in the third activity. This also builds on several short-term efforts. The major problem to be addressed here concerns ways of ascertaining and incorporating the statistical distributions of the various climatic elements of interest to users. Experience with temperature and precipitation, which have different distributions, provides the groundwork, and the earlier research investigations of temporal variability provide additional information. Most elements involved also have many fewer observation sites and a much shorter length of record. Consequently a range of statistical approaches must be tested to ensure that realistic spatial and temporal distributions are produced.

It is also appropriate at this stage to develop a less specific scenario whose primary purpose is the provision of reliable information to the general public in a succinct, comprehensible way. This serves two major purposes. First, it has a general educational role, encouraging wide dissemination of information about the potential impacts of climate change. Second, there is a more specific educational role, in that a succinct scenario should serve as an information source to stimulate people in areas where climate may have an impact, but who are not yet involved in impact assessment, to begin to evaluate the possibilities. Thus it is recommended that this scenario be developed as a Spatial Shift Scenario to provide the needed succinct summary.

In keeping with the general focus on the incorporation of process-based approaches in these medium-term efforts, the first module research area concentrates on the development of links between the physical models of various scales. The nature of the links partly depends on the contemporary status of model development, but efforts must be made both to develop direct links between models and to specify appropriate transfer functions between them in such a way that the needed user-oriented information is produced.

The second area of modular research addresses questions of the spatial distribution of the changed climate. Although some of the efforts discussed previously have a spatial dimension, many are most appropriate for relatively small areas. Hence it is necessary to investigate ways in which

their results can be generalized to provide truly regional scenarios, and at the same time specify the regional boundaries for a particular scenario. Hence it is recommended that a variety of methods, considered both individually and collectively, be used to explore the spatial aspects of scenario development.

A major effort in the "Ancillary Activities" category appropriate at this stage is exploring the documentation needs of scenarios as they are produced. One goal of the EPA program is to provide to people undertaking impact assessments the guidance necessary for them to produce their own scenarios. Consequently, in the light of experience with the first generation scenarios, at this stage it is necessary to begin to stimulate cooperation between the scenario producers and their potential users to provide such documentation.

The second activity in the Ancillary category is a review of the state of the art in the linking of physical and chemical models. This, as with the similar effort in the short-term recommendations, is designed to explore the potential for forging new links during the subsequent generation of scenario development.

LONG-TERM

Long-term efforts involve work in the time horizon of 5+ years, involve third generation scenarios, and are shown in Table 13.

There are two major thrusts for this third generation of scenarios. One is the development of detailed regional scenarios to meet specific user needs. Particular attention is given here to air quality assessments, but it is anticipated that similar approaches will be developed to meet needs in other fields of impacts. The other thrust is to start new initiatives to provide more detailed information in all areas of climatic impact.

The first scenario, a Regional Air Quality Scenario, emphasises regional scale conditions which may persist for several days or weeks. It builds, therefore, on the experience gained through creation of Anomaly and Event Threshold scenarios and the spatial information developed during the previous modular research effort. Newly incorporated are the specific user-oriented regional chemical models (such as ROM) which provide the required assessment information.

TABLE 13: RECOMMENDATIONS FOR LONG-TERM RESEARCH EFFORTS

Scenario Development:

- o Develop Regional Air Quality Scenarios:
  Use: previous Event Threshold Scenario
  previous (Drought) Anomaly Scenario
  Incorporate: Regional Chemistry Models + Spatial Synoptics + Process Transfers

- o Develop Urban Air Pollution Scenarios:
  Use: previous Event Threshold Scenario
  previous Synoptic Event Scenario
  Incorporate: Urban Chemistry Models + Statistical Transfer + Process Transfer

- o Develop Storm Scenarios:
  Use: previous Event Threshold Scenario
  previous Synoptic Event Scenario
  Incorporate: Mesoscale Meteorological Models

- o Develop Linked Regional Scenarios:
  Use: previous scenario outputs (especially Circulation Analysis)
  Incorporate: Teleconnections

Module Research:

- o Explore direct linkages of models for whole scenario:
  Global Models + Regional Models + Mesoscale Models

- o Explore direct linkages for applications other than air quality:
  Process Models + user application models

Ancillary Activities:

- o Oversee use of "self-documenting" scenario by selected users

- o Reassess user needs, identify new users and uses

The second scenario, an Urban Air Pollution Scenario, follows an analogous direction, but emphasizes shorter-term and smaller area phenomena. Here the previously developed Event Threshold and Synoptic Event scenarios provide the basic information. This must be amalgamated with urban chemical models to provide the needed products. On this small urban scale, however, it is anticipated that investigations will rely more on empirical methods for scale linkages, so that previously gained knowledge of statistical transfers will have to be used as an integral part of the process.

The problem of incorporating mesoscale features is tackled directly in the third scenario to be developed. This addresses the needs articulated by users for Storm Scenario information. Although large, synoptic scale storm probability information is available from some earlier Synoptic Event and Event Threshold scenarios, the smaller scale (and frequently more severe) storms could not be included explicitly. Hence the thrust in this scenario is to incorporate the mesoscale meteorological models of such events. However, it is anticipated that this effort represents the beginnings of a larger task if mesoscale events of this type are to be adequately incorporated into scenarios.

There is a similar large agenda implicit in the final scenario effort recommended here, the development of Linked Regional Scenarios. These are simultaneous scenarios for diverse regions. The emphasis throughout the scenario development research so far has been on scenarios for specific purposes in specific regions. However, it is frequently important in impact analysis to consider simultaneous changes in two or more regions. This problem can be approached by using teleconnections techniques. One method would be to develop a scenario for two regions using an approach which stratifies results in terms of a circulation index. From teleconnection considerations, a given circulation index in one region must be reflected by a certain index in the other. Thus the simultaneous scenarios for both regions can be developed. Another approach is to develop scenarios for two different regions entirely independently, even using different methods, and then use teleconnections in a similar way to assess the likelihood of their simultaneous occurrence, to assess their reliability, and to check their "external consistency". Neither approach has been tested, and it is anticipated that this is also the start of a large research task.

The modular research needed during these third generation efforts strongly emphasizes the process modeling approach. It is at this stage that the possibility of complete links at all scales begins to emerge. Although this has most direct relevance to the potential use of mesoscale models in scenarios, the links between models at all scales must be developed and tested.

The other modular research needed is in the development of links between the process models and the application models used in impact assessment. Links between process models and those assessing air quality have been explicitly considered as the first two scenario development efforts of this generation. However, similar links undoubtedly exist for all other applications, and it can be anticipated that forging those links will need as much research as do the climate-chemistry-air quality links. Some of this

research will have been going on throughout the time considered here, both as the result of stimulation following interactions between scenario users and producers within the EPA effort and as research entirely independent of EPA initiatives. However, at this stage it is pertinent to review the efforts in order to develop general concepts and research methodologies for creating links, providing a framework for their more effective development whenever new needs are revealed.

The first major concern within the Ancillary Activities, in fact, is for the identification and development of new users and new user needs. It is anticipated that increasing use of scenarios, together with the publicity given to the results they suggest, will stimulate many new effects research efforts and reveal many new needs. In addition, the ongoing research will uncover new information, which will, in turn, encourage new uses. There is equally likely to be a need for, and the development of, new modules of scenario development techniques. Hence there is a need to continuously monitor not only users and their needs but also climatological research frontiers in order to respond with appropriate techniques for scenario development.

While the first "Other Activity" emphasizes ongoing research, the second emphasizes completing the development of a scenario production method. It involves oversight of the use of a "self-documenting" scenario. The methods developed and documented earlier must be transferred from the research community to those who will use them in an operational setting. Thus this activity is the final stage, allowing for last-minute corrections and adjustments before the method is presented to the user community as an operational scenario development technique.

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APPENDIX A

THE SCENARIO DEVELOPMENT SEMINAR

The seminar series was an outgrowth of the initial project objective to develop ideas for scenario development using both a literature search and contacts with those with existing experience.

The basic strategy was to invite to the Triangle area one "scenario development expert" each week for the Spring Semester, 1989. This expert was requested to present a seminar in the "Scenario Development Seminar" and to spend at least two days in discussions with project personnel. The objective of each visit was to allow an interchange of ideas between the EPA/UNC group and visitors with some experience in the scenario development field. Thus, while a formal presentation was the centerpiece, an important component was time for individual discussions.

The list of speakers was selected to represent a wide range of potential approaches. A series of potential visitors was identified, following an initial literature search and from the knowledge of project personnel. Telephone contacts were then made with a selected group to ascertain willingness to participate and availability dates. The final group, constituting the seminar series, is given in Table A.1.

Although numerous telephone conversations were held with each participant, the emphasis for the seminar was that the speaker address a topic with which he felt comfortable, whether this be previous scenario work or current research activities. The only formal guidance was a brief statement of the objectives of the overall project and a one page summary of the thoughts of the project personnel at the time of writing (December, 1988) (Table A.2). Participants were also asked to furnish a short reading list at least a week prior to their visit, so that seminar participants would have the required background material. Again, the focus of this was left open, so that some people provided references directly applicable to their presentations, while others provided background material without specifically mentioning the detail in their talks.

The enthusiastic cooperation of all those contacted was extremely gratifying. Equally so was the amount of work which had obviously gone into preparation. Unfortunately R. Dickinson had to cancel at the last moment for personal reasons. David Sharon stepped in at the last moment to give a presentation in his place.

Most presentations were video-taped. Copies are available from the authors for the cost of reproduction, and subject to the approval of the participants. No copies are available for Sharon's presentation (at his request since he had no time to really prepare) nor for that of Cohen (owing to technical difficulties).

Interested professional personnel in the Triangle area were invited to attend the seminar. It was originally intended to make the seminar open to all students in the universities of the Triangle area, but initial interest was so high that it was perforce restricted to primarily to UNC students. The background of the participating students varied greatly. Most were graduate students, but backgrounds ranged from no more than a single undergraduate course in physical geography, to those whose Ph.D. dissertation research was directly related to the scenario subject. Participants were drawn mainly from the fields of geography, ecology, atmospheric chemistry and education.

Participating students were expected to keep up with the required readings and participate in discussions. For credit, they were required to develop their own scenario as a term paper. The only constraint on this scenario was that it contained "real" data and was oriented towards a particular application. Project personnel assisted with the provision of data and, for some students, ideas. The resulting scenarios covered an incredibly wide range of topics (Table A.3).

All participants did a large amount of work, but the seminar proved to be a rewarding, interesting, and highly educational experience.

TABLE A.1

Geography 308/Ecology 199 Seminar Schedule

TECHNIQUES FOR THE DEVELOPMENT OF CLIMATE SCENARIOS

Wednesdays, 7 p.m. EPA, Research Triangle Park

Jan. 18	Introduction
25	Peter Lamb
Feb. 1	Stan Grotch
8	Tom Webb
15	Bob Dickinson
22	Dave Moreau
Mar 1	James Friend
8	No meeting - AMS Mtg Charleston SC
15	No meeting - SPRING BREAK
22	Suki Manabe
29	Tom Wigley
Apr 5	Stewart Cohen
12	Tom Karl
19	Ronald Neilson
26	Wrap up

TABLE A.2

THOUGHTS ON SCENARIO BUILDING

To be useful for impact assessment, scenarios must provide the type of information and detail needed by those who will undertake the assessment.

Process models, including GCM's and the emerging regional models, must be used as far as possible since they explicitly incorporate the changed atmospheric composition. However, impact-oriented scenarios commonly require detail beyond that currently reliably available from such models. It is possible to provide such detail using judicious analyses of the historical record of climate. Chemical models and historical chemical records must be included with the physical where appropriate.

The approach we have adopted is to view all previously developed model outputs and analysis techniques as potential "tools". Appropriate tools can be selected, or developed if missing, and linked together to provide the scenario building strategy. General classes of tools have been identified (see below). All tools must be tested for scientific validity and suitability for a particular task. This leads to a set of questions which it would be valuable to discuss in the seminar series:

What are suitable tools?
What are their strengths and weaknesses?
What logical links can be established between tools?
How can the links best be forged?
How can the scientific validity of the tools, links and results be tested?
What research is needed to refine the tools, links and testing?

POTENTIAL CLASSES OF TOOLS FOR SCENARIO DEVELOPMENT

General Circulation Models
Regional Process Models
Mesoscale Models
Microscale Models

Global Chemistry Models
Regional Chemistry Models
Urban Chemistry Models

Synoptic Analyses
Water Budget Analyses
Teleconnections
Weather Generators
Time Series Analyses
Multivariate Techniques
Spatial Analysis Techniques
Probabilistic Methods
Paleoclimatic Information

Climate Inversion Methods
Surface-Circulation Links

TABLE A.3

TOPICS OF STUDENT SCENARIO PRODUCTIONS

The effects of atmospheric carbon dioxide doubling in a southeastern United States wetland: A scenario

Impact of global warming and increased biogenic hydrocarbon emissions on control requirements for attainment of ozone standards

Swampland or dryland: The effect of climate change on the lake levels of the Upper Etonia Creek Water Basin (Florida)

Temperature and precipitation trends, Asheville station, North Carolina, 1983-1988

A simulation study of the impact of global warming on urban ozone formation

Possible increase in tropical storm frequency with a global warming

The effect of a rise in global mean temperature on last spring freeze dates and peach production in Georgia

Climate change and its effect on Antarctic plankton communities

The Triangle area: Are urban heat islands being created?

Peak electrical demand forecasts and implications of climate change for the state of Virginia

Effects of global warming on the sex ratio of the Loggerhead turtle (Caretta caretta): A scenario

Impacts of a 5°C temperature increase on nuisance blue-green algal blooms in North Carolina coastal plains rivers.

Possible effects of global warming on Missouri corn production

A scenario of storm activity in North Carolina

A scenario of future surface temperature and precipitation fields during winter over the eastern half of North Carolina

A preliminary study of extreme temperatures and their relationship to hospitalizations in Houston, Texas

Scenarios of climate change impacts on a local water balance

Skiing in the Sunbelt: Global Warming and the Ski Industry in western North Carolina